Cosmic ray acceleration at supernova remnants

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Supernova remnants (SNRs) are believed to be the source of Galactic cosmic rays (CRs). SNR shocks accelerate CR protons and electrons which reveal key insights into the non-thermal physics by means of their synchrotron and gamma-ray emission. The past years have seen significant progress with particle-in-cell (PIC) simulations of ab-initio diffusive shock acceleration of electrons and protons. Because of numerical limitations, full PIC simulations typically run for a few physical second in one dimension and it is unclear how these results can be extrapolated to astrophysical SNRs. To this end, we perform three-dimensional (3D) magnetohydrodynamics (MHD) simulations where we include CR protons and follow the CR electron spectrum. We adopt several functional forms of the (electron and proton) acceleration efficiencies and magnetic field amplification models from plasma simulations. Comparing the results to observational data enables us to scrutinize the underlying kinetic physics and to connect the SNR with the surrounding interstellar medium.

The remnant SN 1006 is an ideal particle acceleration laboratory because it is observed across all electromagnetic wavelengths from radio to gamma rays. By matching the simulated and observed morphology and non-thermal spectrum of SN 1006 in radio, X-rays and gamma-rays, we gain new insight into CR electron acceleration and magnetic field amplification. 1. We show that a mixed leptonic-hadronic model is responsible for the gamma-ray radiation: while leptonic inverse-Compton emission and hadronic pion-decay emission contribute equally at GeV energies observed by *Fermi*, TeV energies observed by imaging air Cherenkov telescopes are hadronically dominated. 2. We show that quasi-parallel acceleration (i.e., when the shock propagates at a narrow angle to the upstream magnetic field) is preferred for CR electrons and that the electron acceleration efficiency of radio-emitting GeV electrons at quasi-perpendicular shocks is suppressed at least by a factor ten. This precludes extrapolation of current one-dimensional PIC simulations of shock acceleration to realistic SNR conditions. 3. To match the radial emission profiles and the gamma-ray spectrum, we require a volume-filling, turbulently amplified magnetic field and that the Bell-amplified magnetic field is damped in the immediate post-shock region.

We further scrutinize the hadronic scenario of the TeV gamma-ray emission from SNRs originates from decaying pions that are produced in collisions of the interstellar gas and CRs. Using CR-magnetohydrodynamic simulations, we find that large-amplitude density fluctuations of $\delta\rho/\rho > 75$ per cent are required to strongly modulate the gamma-ray emissivity in a straw man's model in which the acceleration efficiency is independent of magnetic obliquity. However, this causes strong corrugations of the shock surface that are ruled out by gamma-ray observations. By contrast, magnetic obliquity-dependent acceleration can easily explain the observed variance in gamma-ray morphologies ranging from SN1006 (with a homogeneous magnetic field) to Vela Junior and RX J1713 (with a turbulent field) in a single model that derives from PIC simulations. This implies that gamma-ray bright regions result from quasi-parallel shocks (i.e., when the shock propagates at a narrow angle to the upstream magnetic field), which are known to efficiently accelerate CR protons, and that gamma-ray dark regions point to quasi-perpendicular shock configurations. Comparison of the simulated gamma-ray morphology to observations allows us to constrain the magnetic coherence scale λ around Vela Jr. and SN1006 to $\lambda \sim 13$ pc and $\lambda > 200$ pc, respectively, where the ambient magnetic field of SN1006 is consistent with being largely homogeneous.

Our work connects micro-scale plasma physics simulations to the scale of SNRs and demonstrates the ability of using TeV gamma-ray morphologies to understand the magnetic coherence scale of the interstellar medium surrounding the SNRs.