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Tracing the origin of low diffusivity and CR bubbles around sources

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1. EXECUTIVE SUMMARY

In the last decade there have been many observations in γ-rays which suggest that within regions of $10 - 100\,\mathrm{pc}$ around stellar clusters, pulsar wind nebulae or SNRs the particles' diffusion coefficient has to be ~ 100 times smaller than the Galactic average diffusion coefficient inferred by secondary-to-primary ratios.
In this work we provide a possible explanation for this suppression for a typical SNR. The novelty in this work is that we show that accelerated particles are able to excite the non-resonant streaming instability after leaving the source. Opposite to the standard picture in which this instability is invoked only at the shock and in the CR precursor, we show that the condition for its excitation is fulfilled also by the particles that left the source and they are able to confine themselves in a large circumsource region. Since the condition for its excitation depends only on the particle flux and the magnetic field, it is easy to understand that the non-resonant instability is excited in the flux tube of escaping particles as long as the magnetic field at the shock and in the tube are of the same order of magnitude, because the fluxes can be shown to be the same in both environments. Its growth inhibits the escape of TeV CRs around their sources and forces them to start diffusing on much smaller scales than expected by the mean Galactic diffusion coefficient. The calculation is performed similar to previous attempts in the flux tube assumption: particles escape the SNR along the local magnetic field line and fill a one dimensional flux tube. Since diffusion perpendicular to the local magnetic field is highly suppressed, the tranverse size of the flux tube is expected to coincide with the extension of the source. As a consequence of the reduced diffusion, we find another important effect. A large pressure gradient with respect to the ambient ISM forms which results in the expansion of the CR flux tube in the transverse direction invalidating the simple flux tube assumption. This overpressurized CR bubble leads to a partial evacuation of the background gas.

After providing analytical estimates we study this effect via two and three dimensional hybrid particle-in-cell simulations. In our simulations we find confirmation of the expectations based on the analytical treatment, i.e. CRs form a bubble in the circumsource region which expands spherically and not only along the local magnetic field lines. Based on our analytical estimates and our simulations we expect that all sufficiently powerful CR sources should be surrounded by extended regions of reduced diffusivity and local overdensity of CR particles.

The existence of these bubbles has many important implications which will be studied in future works. First, due to the enhanced particle trapping close to the source environment CRs can accumulate a significant fraction of their grammage in the source environment. On the other hand, our simulations show the excavation of the background plasma which effectively will counterplay this effect. Without this excavation and a diffusion coefficient reduced by a factor of ~ 100 the source grammage alone would be comparable to the one inferred by observations. Second, the diffusion coefficient of electrons will be reduced as well in the bubble region. Because of their higher energy losses, the escape time might actually become comparable to the loss time leading to a possibly steeper spectrum of electrons and an energy cutoff related to the stronger losses.

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