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Are pulsar halos rare ?

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Extended gamma-ray emission, interpreted as halos formed by the inverse-Compton scattering of ambient photons by electron-positron pairs, is observed towards a number of middle-aged pulsars. The properties of the emission suggest the possibility of a very efficient confinement of the particles over tens of parsec. The physical origin and actual commonness of the phenomenon in the Galaxy remain unclear. The level of diffusion suppression seems extreme compared to what can be achieved in most recent theoretical models.

Using a phenomenological two-zone diffusion framework in the light of Fermi-LAT, HAWC, and AMS-02 data, we searched for model setups minimizing as much as possible the extent and magnitude of diffusion suppression in the halos around J0633+1746 and B0656+14. Extrapolating these descriptions to all other nearby middle-aged pulsars, we show that the resulting combined positron flux including the contribution from Geminga would saturate the AMS-02 measurement above 100GeV for injection efficiencies that are much smaller than those inferred for the canonical halos in J0633+1746 and B0656+14, and more generally with the values typical of younger pulsar wind nebulae. This suggests the possibility that most middle-aged pulsars do not develop halos, with an occurrence rate of the phenomenon possibly being as low as ~5–10%, although the evidence supporting that depends on the actual properties of the local pulsar population and on the uncertain physics driving the formation and evolution of halos.

We searched for complementary evidence for the rarity or commonness of pulsar halos by performing a population synthesis for the Milky Way, with a simple but coherent approach for the PWN-halo evolutionary sequence. Pulsar halos are shown to be viable counterparts to a fraction of the currently unidentified sources if they develop around most middle-aged pulsars, and the number of detectable halos in existing or future surveys ranges from 30 to 80% of the number of detectable PWNe. The level of diffuse emission from unresolved populations in each survey is found to be dominated by halos and comparable to large-scale interstellar radiation powered by cosmic-rays above 0.1–1 TeV. Yet, if pulsar halos are rare, as suggested from the local positron flux constraint, the total number of currently known TeV sources including unidentified ones cannot be accounted for in our model from young PWNe only. This calls for continued efforts to model pulsar-powered emission along the full evolutionary path, including the late stages past the young nebula phase.

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