Pulsar TeV Halos Explain the Diffuse TeV Excess Observed by Milagro

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Milagro observations have found bright, diffuse TeV emission concentrated along the galactic plane of the Milky Way. The intensity and spectrum of this emission is difficult to explain with current models of hadronic γ-ray production, and has been named the "TeV excess." We show that TeV emission from pulsars naturally explains this excess. Recent observations have detected "TeV halos" surrounding pulsars that are either nearby or particularly luminous. Extrapolating this emission to the full population of Milky Way pulsars indicates that the ensemble of "subthreshold" sources necessarily produces bright TeV emission diffusively along the Milky Way plane. Models indicate that the TeV halo γ-ray flux exceeds that from hadronic γ rays above an energy of ~500 GeV. Moreover, the spectrum and intensity of TeV halo emission naturally matches the TeV excess. Finally, we show that upcoming HAWC observations will resolve a significant fraction of the TeV excess into individual TeV halos, conclusively confirming, or ruling out, this model.

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Milagro has detected bright, diffuse TeV γ-ray emission from the Milky Way galactic plane [1]. Early analyses considered the region $40° < \ell < 100°$ and $|b| < 5°$, finding a diffuse γ-ray flux of $(6.4 \pm 1.4 \pm 2.1) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at a median energy of 3.5 TeV. This exceeded predictions by nearly an order of magnitude [2,3], and has been dubbed the TeV excess [2]. Subsequent Milagro observations detected this excess at 15 TeV [4], while no excess was observed at ~1 TeV by ARGO-YBJ [5]. (While the ARGO-YBJ team does not claim any excess compared to the Fermi P7V6 diffuse model, our analysis shows some evidence of an excess compared to GALPROP-based models of diffuse γ-ray emission.) These findings are only consistent if the diffuse TeV γ-ray spectrum becomes significantly harder than the $\alpha = -2.7$ spectrum observed at GeV energies.

Two models have been posited to explain the excess. The first utilizes standard cosmic-ray production, dominated by protons accelerated in supernovae, and modifies cosmic-ray propagation to fit the excess. Work by the GALPROP and Milagro teams found that relaxing local cosmic-ray constraints and renormalizing the γ-ray flux to the EGRET excess [6] allowed hadronic models to fit the data [4]. However, three subsequent observations have challenged this interpretation. First, Fermi disproved the EGRET excess [7], decreasing the 1 GeV γ-ray normalization by ~2. Moreover, Fermi-LAT observations indicate that the cosmic-ray electron injection spectrum breaks from approximately -1.5 to approximately -2.43 at ~3 GV, further decreasing the leptonic diffuse emission compared to [4] by a factor of ~8 [8]. Second, AMS-02 measurements have constrained any hardening of the local cosmic-ray proton spectrum [9]. Third, ARGO-YBJ null observations at ~1 TeV necessitate an unphysically sharp break in the hadronic γ-ray spectrum [5]. We note that the electron spectrum need not be homogeneous, and may be hardened by confined cosmic-ray sources (as in the Cygnus A cocoon [10]). However, these regions are normally small due to their high densities (most of the Cygnus A emission is contained within the point source MGRO J2031 + 41). Moreover, these sources appear subdominant to the larger diffuse background. For example, an analysis of the larger Cygnus complex by the Fermi-LAT collaboration found a diffuse spectrum similar to the galactic mean [11].

A refinement of these models employed spatially variable cosmic-ray diffusion to avoid local cosmic-ray constraints [12]. In this model, the energy index of the diffusion coefficient increases with galactocentric radius, hardening the γ-ray spectrum near the Galactic center without affecting local cosmic rays. This model fits the TeV excess [13], and may provide a better fit to the GeV diffuse γ-ray emission [12]. However, standard cosmic-ray diffusion models also fit the diffuse GeV γ rays to within systematic errors [8]. Thus, this model is best understood as a fit to the Milagro data that is not strongly motivated by external observations.

The second class of models fits the excess with a population of individually subthreshold point sources [2]. This new component has a hard spectrum and exceeds the hadronic γ-ray flux at TeV scales, while remaining subdominant at GeV energies. However, up until now, no source class had been uncovered that could produce the TeV spectrum and intensity. Recently, Observations by the H.E.S.S. and HAWC collaborations found evidence for bright diffuse emission along the galactic plane, but were not able to differentiate between these classes of models [14,15].

We show that pulsars must produce such an emission component. This builds upon existing observations by

Milagro, HAWC [16], and H.E.S.S. [17]. Each telescope has observed bright, spatially extended, emission coincident with energetic pulsars. We show that the ensemble of all pulsars produces a population of individually subthreshold point sources with an integrated γ-ray flux matching the TeV excess intensity. Moreover, the hard pulsar spectrum makes Milagro observations compatible with ARGO-YBJ and Fermi-LAT constraints. Upcoming HAWC observations will resolve many of the pulsars responsible for the TeV excess, imminently testing this model.

TeV Halo observations.—Milagro [18], HAWC [19], and HESS [17] have found TeV sources coincident with numerous Australia Telescope National Facility (ATNF) pulsars [20]. These pulsars have a hard γ-ray spectra ($\sim E^{-2.2}$) consistent with the inverse-Compton scattering of the same e^+e^- that produce x-ray pulsar wind nebula (PWN) [21,22]. They have a γ-ray intensity indicating that $\sim$10% of the pulsar spin-down power is converted into e^+e^- pairs [22]. Finally, these pulsars have radial extents that increase with pulsar age and extend > 10 pc for $\gtrsim$10 kyr pulsars [17]. This contrasts with PWN, which have $\sim$1 pc extents. The TeV emission volume is 1000x larger and requires a new physical model. These sources have been termed TeV halos [23].

Because the pulsar's rotational kinetic energy is the source of all TeV halo emission, the high luminosity of TeV halos constrains every phase of γ-ray generation. Pulsars must convert a significant fraction of their spin-down power into e^+e^- pairs. High-energy ($\gtrsim$10 TeV) e^+e^- must lose most of their energy before exiting the halo. Inverse-Compton scattering must significantly contribute to these energy losses. For the Geminga pulsar, models indicate that between 7% and 29% of the total pulsar spin-down energy is converted into e^+e^- pairs, that $\gtrsim$10 TeV e^+e^- lose more than 85% of their energy before leaving the TeV halo, and that half of this cooling proceeds via inverse-Compton scattering [22].

At present, TeV halos are only observed from a handful of nearby, energetic, pulsars. However, observations suggest that TeV halos are typical in young and middle-aged pulsars. Examining only pulsars over 100 kyr to avoid supernova remnant contamination, we find that the ATNF catalog includes 57 pulsars with reliable distance estimates overlapping the HAWC field of view. Assuming that the TeV luminosity of each system is proportional to the pulsar spin-down power, we produce a ranked list of the expected TeV halo flux. Five of the seven brightest systems are detected by HAWC, while no dimmer pulsars have a TeV association [23]. This is compatible with the assumption that every pulsar has a Geminga-like efficiency. If more distant pulsars produce TeV halos with a similar efficiency, the total contribution from these individually unresolved halos will produce bright, diffuse TeV emission.

Hadronic gamma-ray models.—We first produce a model for the diffuse γ-ray emission from standard astrophysics. We utilize the ensemble of 128 GALPROP models developed by Fermi to explain the diffuse GeV flux [8]. GALPROP physically models the production, propagation, and emission of Milky Way cosmic rays [24,25]. These cosmic rays are dominated by protons accelerated in supernovae; thus, we denote this as a "hadronic background," even though it includes leptonic emission. Contrary to [12,13], these models are not tuned to the TeV excess, making them a natural choice to investigate the TeV halo contribution. While these models span an ensemble of diffusion parameters, they are all fit to the GeV emission and include no new spectral features at TeV energies. Thus, they produce similar TeV fluxes. To model the TeV emission, we extend the maximum cosmic-ray energy to 10 PeV, and the maximum γ-ray energy to 100 TeV, providing a straightforward extrapolation of the Fermi data to TeV energies. Using these models to describe the TeV diffuse background rests on two assumptions: (1) that the Fermi-LAT diffuse emission is well described between $\sim$100 MeV and 100 GeV, and (2) that no new spectral feature alters the extrapolation of this model between 100 GeV and 10 TeV. As there is no evidence (outside the TeV excess) for new TeV cosmic-ray physics, and AMS-02 observations strongly constrain any such feature, this is a well-motivated background model.

Models for the TeV halo flux.—Because GALPROP produces a physical cosmic-ray model, it utilizes the Milky Way supernova rate. This normalizes the pulsar birth rate and thus the TeV halo formation rate. We assume that all supernovae produce pulsars. This is a mild overestimate, but it is degenerate with several assumptions in this study. While pulsars obtain a natal kick at birth [26], a typical kick of $\sim$400 km/s moves a pulsar only $\sim$40 pc over the 100 kyr period during which the TeV halo is brightest. We ignore this effect.

The injected cosmic-ray proton luminosity in GALPROP lies between 0.69 and 1.2×10^{40} erg s^{-1}. Assuming each supernova injects 10^{51} erg, with 10% in cosmic-ray protons, this implies a supernova rate of 0.0021–0.0037 yr^{-1} in the Milagro ROI, and an integrated Milky Way rate of $\sim$0.015 yr^{-1}. This matches the observed supernova rate of 0.019 ± 0.011 yr^{-1} [27].

We produce a steady-state pulsar population normalized to the supernova rate and morphology of each GALPROP model, which themselves utilize the observed distributions of OB stars [28], pulsars [29–31], or supernova remnants [32]. We calculate the γ-ray luminosity for each TeV halo following [33]. Specifically, we pick an initial period following a Gaussian with $\mu_p = 0.3$ s and $\sigma_p = 0.15$ s, and an initial magnetic field following a log Gaussian with $\log_{10}(\mu_B/1\ \mathrm{G}) = 12.65$ and $\sigma_B = 0.55$ [34]. We pick a random pulsar age between 0 and 10 Myr, and spin the pulsar down on a timescale $\tau = 3c^3 I P_0^2 / 4\pi^2 B_0^2 R^6$ [35], assuming $I = 10^{45}$ cm^2 g and $R = 15$ km. The pulsar period evolves following $P(t) = P_0(1 + t/\tau)^{1/2}$, providing a spin-down power $\dot{E} = -[8\pi^4 B_0^2 R^6 / 3c^3 P(t)^4]$ [35].

We assume that 10% of the spin-down power is transferred into e^+e^- pairs above 1 GeV. This is consistent with Geminga observations indicating that 7%–29% of the spin-down power is transferred into e^+e^- [22]. We adopt an e^+e^- injection spectrum following a power law with an exponential cutoff, varying the parameters α and $E_{\rm cut}$ to fit the Milagro data.

These leptons are cooled by inverse-Compton scattering and synchrotron. TeV halos cannot significantly affect the magnetic field or interstellar radiation field (ISRF) throughout their ~10 pc extent [22,23]. We thus adopt an interstellar magnetic field of $B = 3\ \mu$G (0.22 eV cm^{-3}), and ISRF of 1.56 eV cm^{-3}. We subdivide the ISRF into a cosmic microwave background component of 0.26 eV cm^{-3} with a typical energy of 2.3×10^{-4} eV, an infrared component of 0.6 eV cm^{-3} with typical energy 1.73×10^{-3} eV, an optical component of 0.6 eV cm^{-3} with typical energy 0.43 eV, and an UV component of 0.1 eV cm^{-3} with typical energy 1.73 eV [33].

Unlike individual TeV halos, where e^+e^- below ~10 TeV escape before cooling [22], diffuse e^+e^- are further cooled in the interstellar medium. Assuming a standard diffusion constant of $D_0 = 5 \times 10^{28}$ cm^2 s^{-1} at 1 GV and a Kolmogorov index $\delta = 0.33$, e^+e^- travel only 0.38 kpc ($E^{-0.33}$/1 GeV) before losing energy, implying that $e^+e^- \gtrsim 50$ GeV cool before leaving the plane. Because we consider only TeV emission, we assume that the e^+e^- population is fully cooled. We then calculate the inverse-Compton scattering γ-ray spectrum and intensity taking into account Klein-Nishina effects [33,36].

Our model could produce a single extremely bright TeV halo that would dominate the diffuse emission. However, Milagro would have resolved such a source. Thus, we exclude contributions from any individual halo with a γ-ray flux exceeding Geminga (4.27×10^{-9} erg cm^{-2} s^{-1}), which was barely resolved by Milagro [18]. Our model indicates that only ~1 such source should exist in the ROI, consistent with Poisson fluctuations.

Results.—In Figs. 1 and 2, we show the key result of this Letter. Above ~500 GeV, the diffuse γ-ray flux from leptonic TeV halos exceeds the diffuse hadronic flux. For Milagro data at 3.5 and 15 TeV, TeV halos outshine the diffuse background by factors of ~3 and ~8, respectively. The hard spectrum of TeV halos fits both the Milagro excess and the dimmer ~400–1700 GeV γ-ray flux observed by ARGO-YBJ. (We warn the reader that the differing point-source sensitivities and analysis techniques may affect the relative fluxes observed by ARGO-YBJ and Milagro; see [5].) This is intriguing because hadronic processes cannot simultaneously explain both observations without invoking unphysical breaks in the TeV proton spectrum. We do not show relevant (but less sensitive) results from Whipple [37], HEGRA [38], TIBET-II, or TIBET-III [39]. Our model is consistent with these limits. PeV γ-ray constraints from CASA-MIA [40] and

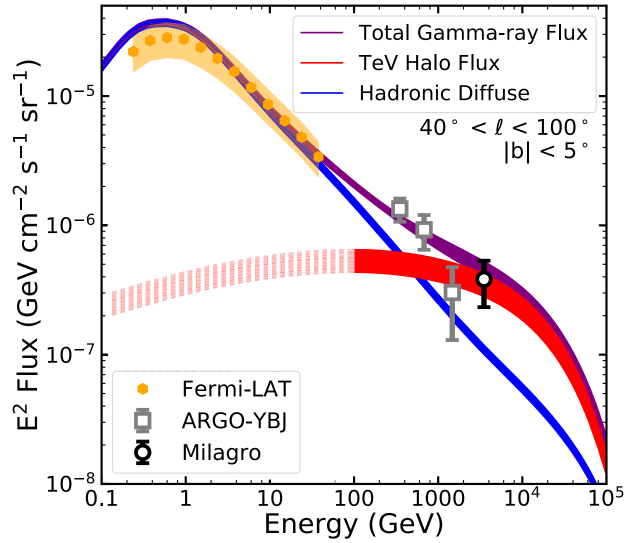

FIG. 1. The contribution of subthreshold TeV halos to the diffuse γ-ray emission along the galactic plane in the region $40° < \ell < 100°$, and $|b| < 5°$, compared to observations by the Fermi-LAT (described in the text), ARGO-YBJ [5], and Milagro [1]. The background (blue) corresponds to the predictions of 128 GALPROP models of diffuse γ-ray emission [8]. The contribution from TeV halos (red) is described in the text. TeV halos naturally reproduce the TeV excess observed by Milagro, while remaining consistent with ARGO-YBJ observations. The dashed red region indicates our ignorance of low-energy γ-ray emission from TeV halos.

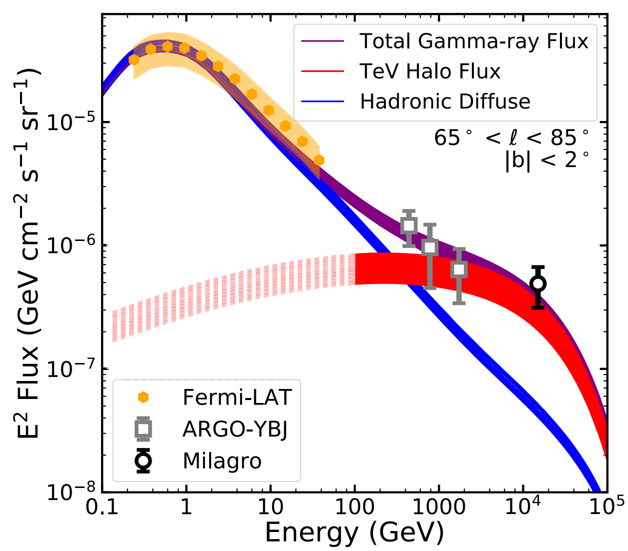

FIG. 2. Same as Fig. 1 in the smaller region $65° < \ell < 85°$, and $|b| < 2°$ examined by Milagro [4] at a higher energy of 15 TeV, as well as ARGO-YBJ [5]. ARGO-YBJ observations are quoted in the latitude range $|b| < 5°$. We renormalize the ARGO-YBJ points based on the ratio of the modeled GALPROP diffuse emission flux in the $|b| < 2°$ and $|b| < 5°$ ROIs, which increases the flux of the three ARGO-YBJ points by 38%, 40%, and 42%, respectively.

KASCADE [41] would be relevant if we did not exponentially suppress the e^+e^- injection above 100 TeV. This cutoff is physically motivated by PWN acceleration models [35] and preferred by Geminga observations [22].

To calculate the diffuse GeV γ-ray flux, we analyze 8.5 yr of Fermi data using standard cuts. We calculate the Pass 8 diffuse model flux in the region $40° < \ell < 100°$, and $|b| < 5°$, allowing the normalization of all 3FGL sources and diffuse components to vary in 0.1° angular bins and five energy bins per decade. Because the statistical errors are tiny, we show 30% systematic error bands corresponding to uncertainties in the Fermi effective area and energy reconstruction [8]. In the smaller ROI, we renormalize our results from the larger ROI based on the relative diffuse emission intensity at 1 GeV.

Our model utilizes a power-law electron injection spectrum $\alpha = 1.7$ with $E_{cut} = 100$ TeV. This is slightly harder than that required to fit HAWC observations of Geminga ($1.5 < \alpha < 1.9$; 35 TeV $< E_{cut} <$ 60 TeV) [22] or the diffuse Galactic center γ-ray emission observed by HESS ($\alpha = 2.2$; $E_{cut} = 100$ TeV) [33]. This e^+e^- injection spectrum is driven by Milagro observations at 15 TeV in the smaller ROI, which is hard to fit with an e^+e^- spectrum that is exponentially suppressed at ~50 TeV. The e^+e^- injection spectrum is degenerate with both the efficiency of electron cooling in the Milky Way plane and the strength of the interstellar magnetic field. Additional observations are necessary to determine the average value of the electron injection spectrum.

Our model calculates the fluxes of individual TeV halos that contribute to the excess. In Fig. 3 we show the differential contribution to the TeV halo number density and total TeV halo flux as a function of the individual γ-ray flux of TeV halos in the $40° < \ell < 100°$, $|b| < 5°$ ROI. Because we are considering the emission from individual halos, we show the differential flux at 7 TeV (corresponding to the 2HWC catalog [19]). The flux of each TeV halo is calculated assuming that it converts the same fraction of its spin-down power into 7 TeV γ-ray emission as Geminga [22,23].

We note three results. First, our model correctly predicts that $\mathcal{O}(1)$ TeV halo as bright as Geminga should exist in the Milagro ROI. In fact, three sources brighter than Geminga are observed by HAWC in this region: 2HWC J2031+415, 2HWC J2019+367, and 2HWC J1908+063. All three are spatially extended and overlap known ATNF pulsars. They are all TeV halo candidates [23], though we note that the latter two sources are young pulsars where TeV γ-ray emission may also be produced by supernova remnants. Second, we find that 10 yr HAWC observations will definitively test our model, finding ~50 individual TeV halos in the Milagro ROI. Third, we find that most of the TeV excess is produced by systems that individually exceed 1% of the Geminga flux. Our model thus provides a clear, testable hypothesis: a significant fraction of the TeV excess will be resolved into individual TeV halos by HAWC observations. Intriguingly, some of these halos may have been already detected. In particular, four sources dimmer than Geminga have been observed in the smaller ROI by VERITAS and HAWC: VER J2019+368 (associated with PSR J2021+3651 [42]), 2HWC J2006+341 (currently unassociated [19]), 2HWC J1953+294 (potentially associated with pulsar DA 495 [19]), and 2HWC J1955+285 (associated either with PSR J1954+2836 or its associated SNR G065.1+00.6 [19]).

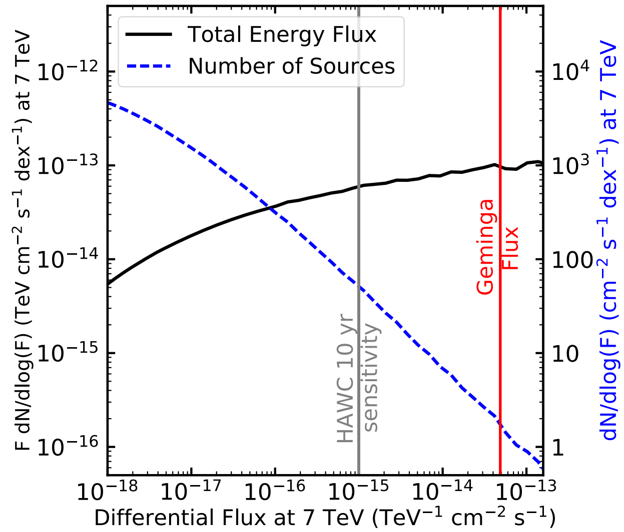

FIG. 3. The contribution of individual TeV halos to the TeV excess in the region $40° < \ell < 100°$, and $|b| < 5°$. We normalize our results at 7 TeV [19], assuming that individual TeV halos convert their spin-down luminosity into 7 TeV γ rays with an identical efficiency as Geminga. Vertical lines correspond to the flux of Geminga, and the projected 10 yr HAWC sensitivity. Results are shown for the total γ-ray flux [$FdN/d\log_{10}(F)$, black, left y axis], which indicates that most of the γ-ray intensity stems from the bright TeV halos, as well as for the source count [$dN/d\log_{10}(F)$, blue, right y axis], which indicates that 10 yr HAWC data will observe ~50 TeV halos in the ROI. For illustrative purposes, in this plot we show the contribution from TeV halos with individual fluxes exceeding Geminga, predicting the existence of only ~1 such system.

Conclusions.—In this Letter, we assumed that the TeV emission from Geminga is typical of young and middle-aged pulsars. This hypothesis is supported by the observation of $\mathcal{O}(10)$ TeV halos similar to Geminga. We have assumed that all pulsars convert ~10% of their spin-down power to relativistic e^+e^-, which subsequently cool via inverse-Compton scattering. We find that these pulsars must produce a population of subthreshold TeV halos that produce a diffuse TeV γ-ray flux. The total flux from these halos exceeds that from hadronic cosmic rays above ~500 GeV. The intensity and spectrum of this emission matches the Milagro excess, and removes the tension between the soft proton spectrum measured by local cosmic-ray experiments and the hard γ-ray spectrum required by Milagro [13].

This result may also have implications for the origin of IceCube neutrinos [43,44]. Rapidly star-forming galaxies (SFG) are a leading candidate [45–56], though recent studies of cosmological star formation have argued against such an interpretation [57]. Because no TeV emission has been observed from SFGs, their very-high energy neutrino flux is extrapolated from Fermi observations, typically assuming a purely hadronic model. Our results indicate that TeV halos produce a hard-spectrum GeV flux, decreasing the normalization and softening the spectrum of the hadronic component. Thus, TeV halos necessarily decrease the SFG neutrino flux. However, the magnitude of this effect is unknown, particularly in the case of the most intense SFGs, which are likely to be "calorimetric" to cosmic-ray protons, with a hadronic γ-ray flux that significantly outshines the TeV halo component [56]. On the other hand, because current SFG models already indicate a best-fit γ-ray spectrum that is somewhat too soft to explain the IceCube signal ($\alpha = -2.3$ [53,56]), any contribution from a hard-spectrum leptonic component, such as TeV halos, makes SFG interpretations of the IceCube signal increasingly untenable.

Finally, we stress that this model is imminently testable. Our analysis predicts that most TeV γ-ray sources are TeV halos [23], and that 10 yr HAWC observations will observe $\mathcal{O}(50)$ TeV halos coincident with radio pulsars [23]. These observations will resolve a significant fraction of the TeV excess into individual halos, clearly confirming, or ruling out, the TeV halo origin of the Milagro excess.

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