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UNDERSTANDING THE DIFFUSE GAMMA RAY EMISSION OF THE MILKY WAY – FROM SUPERNOVA REMNANTS TO DARK MATTER

ABSTRACT: Diffuse gamma ray emission from the Galactic center at 2–3 GeV, as well as the 12 TeV gamma ray excess in the Galactic disk, remain open for debate and represent the missing puzzles in the complete picture of the high-energy Milky Way sky. Our papers emphasize the importance of understanding all of the populations that contribute to the diffuse gamma background in order to discriminate between the astrophysical sources such as supernova remnants and pulsars, and something that is expected to be seen in gamma rays and is much more exotic – dark matter. We analyze two separate data sets that have been measured in different energy ranges from the "Fermi-LAT" and "Milagro" telescopes, using these as a powerful tool to limit and test our analytical source population models. We model supernova remnants and pulsars, estimating the number of still undetected ones that contribute to the diffuse background, trying to explain both the Galactic center and the 12 TeV excess. Furthermore, we aim to predict the number of soon to be detected sources with new telescopes, such as the "HAWC".

KEYWORDS: diffuse background, gamma rays, supernova remnants, pulsars, dark matter

INTRODUCTION

Our current understanding of the overall gamma ray emission of our Galaxy, the Milky Way, relies a lot on findings from different ground based and satellite telescopes. One of the largest contributors to the gamma ray image of the sky is most definitely the Fermi telescope**, specifically the LAT part of

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** The official Fermi Telescope page: https://fermi.gsfc.nasa.gov

the satellite that provided us with the best whole-sky gamma-ray image. From these findings we are able to categorize the emission into several contributing categories – point sources (Galactic and extragalactic), Fermi bubbles and the diffuse emission. If we compare everything measured by the instruments with the models of sources we have, ideally, we should be able to account for the entire gamma-ray emission. The reality is somewhat different – we can discriminate between the modeled Fermi bubbles and resolved point sources, as well as modeled diffuse emission, but after subtracting all these, what we are left with is the unresolved diffuse background – a collection of still unresolved sources and potential exotic contributors such as dark matter.

The Galactic diffuse emission is mostly produced in the interactions of cosmic rays in the interstellar medium (ISM). Another potential sources of gamma rays in the Galaxy could be the illusive dark matter. Some of the mainstream theories of what exactly dark matter is allow for a process of self-annihilation of dark matter particles, in places of sufficient densities, which could produce gamma rays of different energies depending on the mass of the annihilating particles. This signal, if existing, should be mixed into the diffuse background, and rather weak one, having in mind that the self-annihilating process is rare. What is fortunate is that there are indications where we should look for such a signal. Places where dark matter gamma ray signal should be most likely detected are places of the largest dark matter densities, and one of such places is the Galactic Centre (GC) (Petrovic et al., 2014).

Indirect dark matter searches have been fueled by better understanding the diffuse emission and the data collected by Fermi LAT. In 2014, Daylan et al. (Daylan et al., 2014) published a paper claiming they have found a spherically symmetric signal from around the GC (1.5 kpc), that peaks at 1–3 GeV that could be fitted with a dark matter map with a 40σ significance. This initiated a series of papers devoted to what was named the "GC excess" that gave other possible explanations such as a bursting source and millisecond pulsars (Petrovic et al., 2014, 2014). The searches continued and were even spread to our neighboring galaxy – M31, which seems to show a similar signal around its center (Eckner et al., 2017).

What has become obvious is that the indirect dark matter searches have two prerequisites for success – new telescopes with better angular and energy resolution and deep understating of all of the other diffuse gamma contributors. Our aim is to study source populations of different kinds that all contribute to the diffuse background and could thus resent a foreground to the dark matter signal, and also giving explanations to the open questions such as the GC excess and the Milagro TeV excess, which will be discussed in detail in the next section.

METHODS

As previously mentioned, there are still open questions when considering the diffuse gamma ray emission of the Mliky Way. One such issue has been the Galactic center excess problem that still remains open for debate and awaits better telescopes that could give the final verdict whether these gamma rays come from astrophysical sources such as millisecond pulsars or dark matter.

Another rather interesting topic is the Milagro TeV excess, a still unexplained high energy flux of gamma rays equaling to $23.1\pm4.5\times10^{-13}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1} 12 TeV, that has been measured by the Milagro telescope in the Galactic coordinate region $-2° < b < 2°$, $30° < l < 65°$ (Abdo et al., 2008).

This excess was first detected in the light of EGRET data in 2006 (Prodanovic, 2006). We have now used the latest Fermi LAT data to see if the situation has changed and if the excess is still present and cannot be accounted for by the known and expected source populations from the LAT 4FGL* catalogue – the latest Fermi catalogue of point sources.

One of the issues when considering a high-energy excess such as the Milagro one, is the fact that the Fermi LAT diffuse model does not reach such high energies and has to be extrapolated to check whether it can explain the 12 TeV point, emphasizing the necessity for telescopes that can operate in the high energy mode. After extrapolation, the excess remains present with a flux of 4×10^{-12} photons TeV^{-1} cm^{-2} s^{-1} sr^{-1}. We have also tested the measured flux against the point sources that have been resolved and are available in the Fermi LAT and TeVCat** catalogues, covering the GeV and the TeV energies, while also conducting a search for GeV-TeV point source counterparts. Even after all of the known GeV and TeV sources are subtracted, along with the diffuse emission we have from the Fermi LAT, the 12 GeV data point remains incompletely explained.

RESULTS

Our idea is to model populations of unresolved astrophysical sources such as pulsars, pulsar wind nebulae (PWN) and supernova remnants (SNR) that could potentially explain this excess measured by Milagro as they are sources of gamma-rays in our Galaxy. These sources are potentially still undetected and remain hidden and contributing to the diffuse background, which is why they are not present in current catalogues.

The number of such sources can be derived from the spatial distribution that is constructed based on current observational and theoretical data for all relevant source populations – SNRs, PWNs and pulsars. Here it should be noted that PWNs and pulsars can practically be treated as one source category as they follow the same distribution and PWN, of course, cannot exist without their fueling mechanisms which are pulsars (Fermi LAT collab. & PTC 2010).

We can calculate the number of potential sources in the Milagro region-of-interest (ROI) where the excess is present, and check whether these can potentially account for the excess emission. For example, for SNR we use the exponential spatial distribution (Green, 2015):

* https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilpsc.html
** http://tevcat.uchicago.edu

$$f_{SNR}\,(r) = (\frac{r}{r_*})^{\alpha}\; exp\,(\frac{r - r_*}{r_*}) \qquad (1)$$

where γ is the galactocentric distance, and γ_* is the galactocentric distance of the Sun (8.5 kpc), and a power-law flux with an exponential cut-off (E_{cut}) at 12 TeV (Fermi-LAT collab. 2019):

$$F \propto E^{-r}\; exp\,(\frac{E}{E_{cut}}) \qquad (2)$$

to derive a total gamma-ray flux of all potentially unresolved SNRs in the Milagro ROI and compare it to the measured Milagro flux, as well as the diffuse gamma-ray background from Fermi LAT and all known point sources. We can calculate the given population flux if we know the luminosity function of a certain population or if we treat the luminosity as a parameter of a certain value. For this value we choose the maximal and minimal luminosities of known and measured SNRs to have the broadest picture of this source population (Fermi-LAT collab. 2019). What we use as a free parameter is the Γ spectral parameter that can vary from source to source. We limit the variation from 1.5 to 2.5 which are the limits in which most of the SNR Γ-value resides (for sources that appear in catalogues such as the 4FGL).

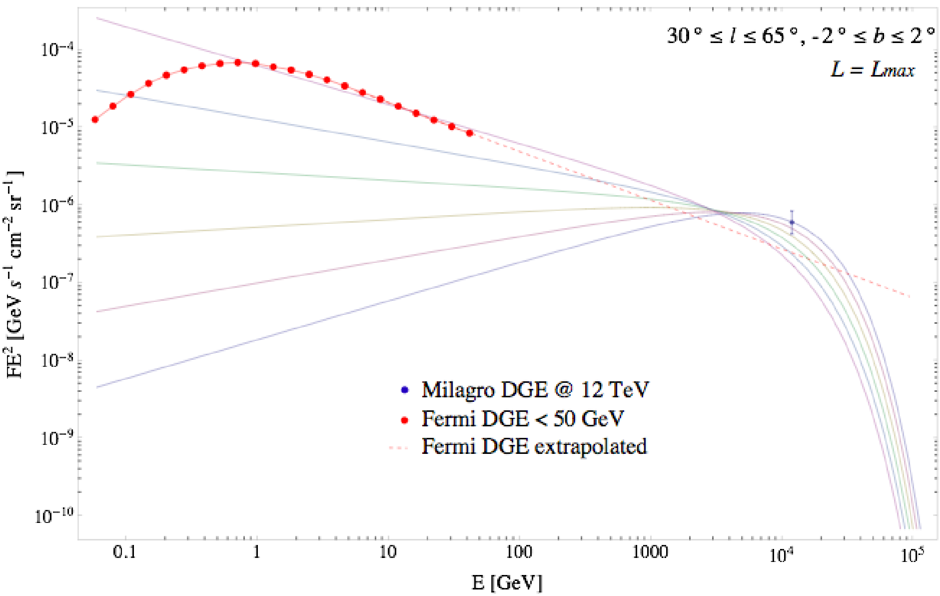

Figure 1. Modeled emission of the unresolved population of SNRS of maximal luminosity residing in the Milagro region of interest. We show the total population gamma ray flux compared to the Fermi measurements up to 50 GeV (red dots), extrapolated to high energies (red dashed line) and the Milagro excess data point (blue). We vary the spectral index of the population from 1.5 to 2.5.

On Figure 1. we present a population of SNR in the Milagro ROI (multi-color lines) with a given spatial and spectral distributions, as well as the Milagro data point and the Fermi diffuse background measurements (data points up to 50 GeV and high-energy extrapolation) in red. The luminosity is of the order of 10^{36} GeV s^{-1}.

As can been seen in the Figure 1. such a population of SNRs can successfully reach the Milagro data point and potentially explain this excess in gamma rays for values of the spectral index on the lower limit end (1.5–1.9), without disrupting the existing image of the diffuse background measured by Fermi LAT.

DISCUSSION

Next steps involve theoretical predictions for other mentioned sources – pulsars and PWNs and seeing how they compare to the detected Milagro flux.

What can be added into consideration is how many of these potentially undetected sources can, and possibly will be, detected by the newest telescopes commissioned to look at the wide energy range gamma-ray sky. One such telescope is the HAWC telescope* that covers the 100 GeV – 100 TeV energy range, thus being a great candidate to solve the Milagro excess mystery. By using the angular (0.1° for energies > 10 TeV) and energy resolution (below 50% above 10 TeV) of HAWC we can predict the number of postulated sources that can be seen by HAWC. This is the topic of our future work that is currently in preparation and can hopefully give us more insight in what is the actual nature of this excess.

CONCLUSION

From what can be seen in this overview, it is clear that the next step needs to be employing better gamma ray detectors both sky and ground based. The HAWC telescope is a big leap forward and after it has collected a substantial amount of data we should we able to draw better conclusions on what the GC excess and Milagro excess actually are.

There is a need for detectors with better both angular and energy resolution that can both peer into the GC at low energies, but also do all sky observations on energies that range from a few GeV to a few tens of TeV in order to get a complete picture of the gamma ray sky.

We need to understand all the astrophysical sources to the best of our abilities in order to be able to disentangle them from the long awaited dark matter signal.

* https://www.hawc-observatory.org

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РАЗУМЕВАЊЕ ДИФУЗНЕ ЕМИСИЈЕ ГАМА-ЗРАЧЕЊА МЛЕЧНОГ ПУТА – ОД ОСТАТАКА СУПЕРНОВИХ ДО ТАМНЕ МАТЕРИЈЕ

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РЕЗИМЕ: Дифузно гама зрачење из центра наше галаксије на енергијама од 2–3 GeV, као и вишак зрачења на 12 TeV у региону галактичког диска још увек су отворена питања која нас деле од комплетне слике високоенергијског зрачења Млечног пута. Наши радови акцентују битност разумевања свих популација извора који доприносе овом зрачењу у циљу разликовања астрофизичких извора попут пулсара и супернових и нечега што би такође требало да остави отисак на гама небу – а то је тамна материја. Анализирамо податке са „Fermi-LAT" и „Milagro" телескопа, где помоћу два сета мерења у два различита енергијска опсега лимитирамо и тестирамо наше аналитичке моделе различитих популација. Моделујемо пре свега остатке супернових, пулсаре и милисекунд пулсаре, те процењујемо који број наведених извора још увек измиче детекцији и учествује у неразлученој гама позадини, истовремено покушавајући да дамо одговор шта то сачињава вишкове зрачења у центру галаксије и на 12 TeV у диску. Такође, циљ нам је и предвиђање броја детектованих извора у блиској будућности помоћу нових телескопа какав је телескоп „HAWC".

КЉУЧНЕ РЕЧИ: дифузно гама позадинско зрачење, гама-зраци, остаци супернових, пулсари, тамна материја