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Egret excess of diffuse galactic gamma rays as tracer of Dark Matter

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The public data from the EGRET space telescope on diffuse galactic gamma rays in the energy range from 0.1 to 10 GeV are reanalyzed with the purpose of searching for signals of Dark Matter annihilation (DMA). The analysis confirms the previously observed excess for energies above 1 GeV in comparison with the expectations from conventional galactic models. In addition, the excess was found to show all the key features of a signal from Dark Matter Annihilation (DMA): a) the excess is observable in all sky directions and has the same shape everywhere, thus pointing to a common source; b) the shape corresponds to the expected spectrum of the annihilation of non-relativistic massive particles into neutral π_0 mesons, which decay into photons. From the energy spectrum of the excess we deduce a WIMP mass between 50 and 100 GeV, while from the intensity of the excess in all sky directions the shape of the halo could be reconstructed. The DM halo is consistent with an almost spherical isothermal profile with substructure in the glactic plane in the form of toroidal rings at 4 and 14 kpc from the centre. This rings lead to a peculiar shape of the rotation curve, in agreement with the data, which proves that the EGRET excess traces the Dark Matter.

1. Introduction

Cold Dark Matter (CDM) makes up 23% of the energy of the universe, as deduced from the WMAP measurements of the temperature anisotropies in the Cosmic Microwave Background, in combination with data on the Hubble expansion and the density fluctuations in the universe (1). The Dark Matter has to be much more widely distributed than the visible matter, since the rotation speeds do not fall off like $1/\sqrt{r}$, as expected from the visible matter in the centre, but stay more or less constant as function of distance. For a "flat" rotation curve the DM has to fall off slowly like $1/r^2$ instead of the exponential drop-off for the visible matter. The fact that the DM is distributed over large distances implies that its properties must be quite different from the visible matter, since the latter clumps in the centre owing to its rapid loss of kinetic energy by the electromagnetic and strong interactions after infall into the centre. Since the DM apparently undergoes little energy loss, it can have at most weak interactions. In addition its mass is probably large, since it cannot be produced with present accelerators. Therefore it is generically called a WIMP, a Weakly Interacting Massive Particle.

Weakly interacting particles can annihilate, yielding predominantly quark-antiquark pairs in the final state, which hadronize into mesons and baryons. The stable decay and fragmentation products are neutrinos, photons, protons, antiprotons, electrons and positrons. From these, the protons and electrons disappear in the sea of many matter particles in the universe, but the photons and antimatter particles may be detectable above the background, generated by particle interactions. Such searches for indirect Dark Matter detection have been actively pursued, see e.g the review by Bergström (2) or more recently by Bertone, Hooper and Silk (3).

The present analysis on diffuse galactic gamma rays differs from previous ones by considering simultaneously the complete sky map *and* the energy spectrum, which allows us to constrain both the halo distribution *and* the WIMP mass. More details have been given elsewhere (4; 5; 6; 7).

In the early universe all particles were produced abundantly and were in thermal equilibrium through annihilation and production processes. At temperatures below the mass of the WIMPS the number density drops exponentially. The annihilation rate $\Gamma = <\sigma v> n_\chi$ drops exponentially as well, and if it drops below the expansion rate, the WIMP's cease to annihilate. They fall out of equilibrium (freeze-out) at a temperature of about $m_\chi/22$ (8). For the present value of $\Omega_\chi h^2 = 0.113 \pm 0.009$ the thermally averaged total cross section at the freeze-out temperature of $m_\chi/22$ must have been around $2 \cdot 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ (9). The observed annihilation rate will be compared with this generic cross section, which basically only depends on the expansion rate of the universe, i.e. on the value of the Hubble constant. However, it should be noted that this cross section may be energy dependent and the annihilation cross section in the present universe may be much smaller than the value deduced from the time of freeze out, when the temperature was $m_\chi/22 \approx$ several GeV. On the other hand the annihilation rate may be enhanced by the clustering of DM in "microhaloes", which increases the density locally. This unknown enhancement factor, usually called "boost factor", may vary from a few to a few thousand (10; 11). Given the uncertainty in the prediction of the boost factor, this can only be obtained from the data by keeping the normalization as free parameter.

2. Indirect Dark Matter Detection

The neutral particles play a very special role for indirect DM searches, since they point back to the source. The charged particles change their direction by the interstellar magnetic fields, energy losses and scattering. Therefore the gamma rays provide a perfect means to reconstruct the intensity (halo) profile of the DM by observing the intensity of the gamma ray emissions in the various sky directions. Of course, this assumes that one can distinguish the gamma rays from DM annihilation from the background, which is dominated by proton-proton interactions for gamma ray energies above 0.1 GeV. Both for DMA and pp collisions the gamma rays originate mainly from the decay of neutral pions, a light particle produced abundantly in the hadronization process of quarks into hadrons. However, the protons in the galaxies and consequently the quarks inside the protons have a steeply falling energy spectrum ($N \propto E^{-2.7}$). In contrast, the quarks from DM annihilation are mono-energetic, since the WIMPS annihilate almost at rest, so their mass is converted into kinetic energy of the quarks. Each quark thus obtains an energy corresponding to the mass of the WIMP, which yields a gamma ray spectrum with a sharp cut-off at the mass of the WIMP. So from the shape of the spectrum the WIMP mass can be deduced. The difference in spectral shape between DMA and background allows to obtain their absolute normalizations by fitting their shapes to the EGRET data. These shapes are well known from accelerator experiments and can be obtained e.g. from the PYTHIA code for quark fragmentation (12); the parameters in this code have been optimized to fit a wide variety of accelerator data with a single model, the string fragmentation model. The fit of the normalizations can be repeated in many different sky direction to obtain the halo profile of the DM. Given the WIMP *number density* in all directions from the flux of the excess and the WIMP *mass* from the spectrum allows to reconstruct the DM mass distribution in our galaxy, which in turn can be used to reconstruct the rotation curve.

A very detailed gamma ray distribution over the whole sky was obtained by the Energetic Gamma Ray Emission Telescope EGRET, one of the four instruments on the Compton Gamma Ray Observatory CGRO, which collected data during nine years, from 1991 to 2000. The EGRET telescope was carefully calibrated in the energy range of 0.02 to 10 GeV (13). It was already noticed in 1997 that the EGRET data showed an excess of gamma ray fluxes for energies above 1 GeV if compared with conventional galactic models (14).

Fitting the three contributions of galactic background, extragalactic background and DMA to the energy spectra of 180 independent sky directions yielded astonishingly good fits with the free normalization of the background agreeing reasonably well with the absolute predictions of the galactic models (15; 16) for the energies between 0.1 and 0.5 GeV. Above these energies a clear contribution from Dark Matter annihilation is needed, but the excess in different sky directions can be explained by a single WIMP mass. The fits for 3 different sky directions are shown in Fig. 1.

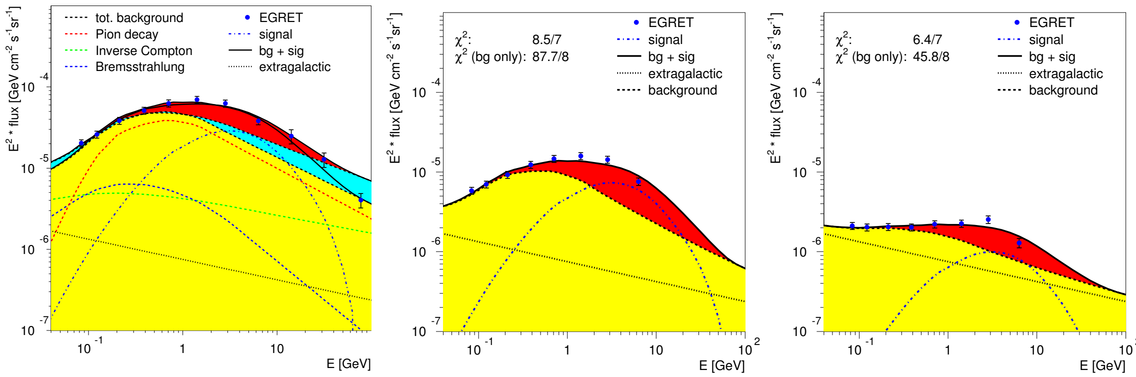

Figure 1. The diffuse gamma-ray energy spectrum of 3 angular regions: from left to right: towards the galactic centre (latitudes $0° < |b| < 5°$; longitudes $0° < |l| < 30°$), the galactic anticentre ($0° < |b| < 10°$; $90° < |l| < 270°$)and the pole regions ($60° < |b| < 90°$; $0° < |l| < 360°$), as measured by the EGRET space telescope. In the two panels on the right the solid straight line represents the fitted contribution from the extragalactic background, while the dotted line indicates the contribution from the annihilation from 65 GeV WIMPs. The total background (DMA) is indicated by the light (yellow) (dark (red)) shaded area, respectively. In the panel on the left the three data points above 10 GeV are for illustrative purposes. They were taken from Ref. (17), but due to the unknown systematic errors, they were not included in the fit. The various contributions to the background are indicated as well, while the uncertainties from the background are indicated by the medium shaded (blue) area. Here the upper edge of the medium shaded (blue) area corresponds the hardest spectrum from Kamae et al. (18) with the power index of 2.5, while the lower edge corresponds to the shape of the conventional GALPROP model (17). Note that since the background normalization is left free, the low energy data (where only the background contributes) are always well fitted and different shapes only show up at larger energies.

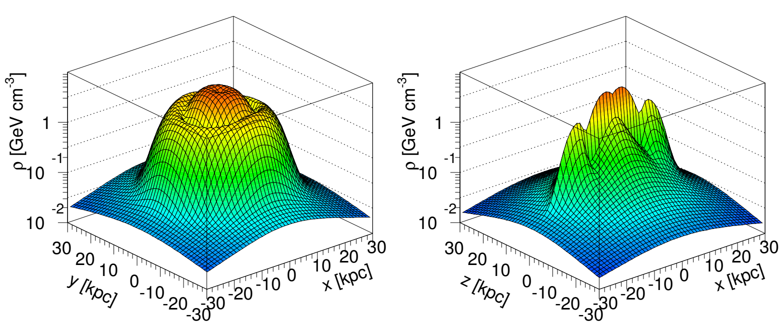

Figure 2. 3D-distributions of the haloprofile in the galactic xy-plane (left) and xz-plane (right). The ring structures at 4 and 14 kpc can be clearly seen.

Other ways to increase the excess would be to harden the spectra of the primary nuclei and electrons with respect to the locally measured spectra. Inhomogeneities in the spectra could happen e.g. by density fluctuations from the spiral arms or Supernovae explosions. However, such models do not describe the shape of the data very well, as can be seen e.g. from Fig. 9 of the so-called optimized model (17), which gives the best fit to the data so far, but still at energies above 2 GeV the model is below the data. Summing over more than 1400 data

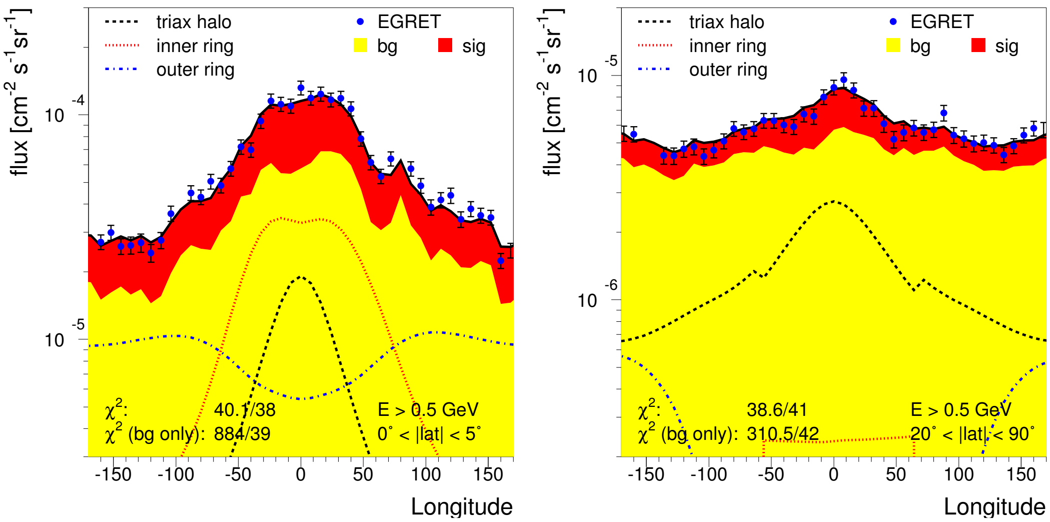

Figure 3. The longitude distribution of diffuse gamma-rays in the disk of the galaxy (left) and towards the galactic poles (right). The contributions of the inner ring, outer ring and isothermal triaxial halo to the excess in the disk can be clearly seen. The points represent the EGRET data.

points in 180 independent sky directions yields a probability for the fit of the spectral shape from the optimized model below 10^{-7}, if the error correlations between the different energy bands are taken into account. Details can be found elsewhere (6; 7). The problem of models without DMA: if the shape of the EGRET excess can be explained perfectly in all sky directions by a gamma contribution originating from the fragmentation of mono-energetic quarks, it is very difficult to replace such a contribution by an excess from nuclei (quarks) (or electrons) with a steeply falling energy spectrum.

From the excess in the various sky directions one can obtain the halo profile under the assumption that the clustering of the DM is similar in all sky directions. This is not necessarily true, since near the centre of the galaxy clumps may be tidally disrupted by the fly by of stars. The annihilation rate is in general proportional to $B\rho^n$, where B is the boost factor and n is between 1 and 2, depending on how much of the DM is clustered (n=2 for no clustering and n=1 if all DM is in clusters). Consequently one has many alternatives to fit, which are outside the scope of the present paper. Therefore we concentrate on a boost factor independent of r and $n = 2$, which turns out to yield a good fit.

The result is surprising: in addition to the isothermal profile the EGRET excess show a substructure in the form of toroidal rings at 4 and 14 kpc, as shown in Fig. 2: on the left hand side the contribution from the $1/r^2$ profile is shown, while for the right hand side the ring structure is added. Such enhanced gamma radiation at 4 and 14 kpc was already observed in the original paper on the EGRET excess (14). Note that the appearance of substructure would also be obtained if a radial dependence of n and B would have been taken. The analysis is sensitive to the radii of ringlike structures, since we are not located at the centre: assuming a constant flux along the ring yields automatically more flux from the nearest parts. The need for these additional rings is most easily seen by comparing the longitudinal profiles in the galactic plane and towards the galactic poles, as shown in Fig. 3. Note that for each bin only the flux integrated for data above 0.5 GeV has been plotted.

The position and shape of the outer ring coincides with the ring of stars, discovered in 2003 by several groups

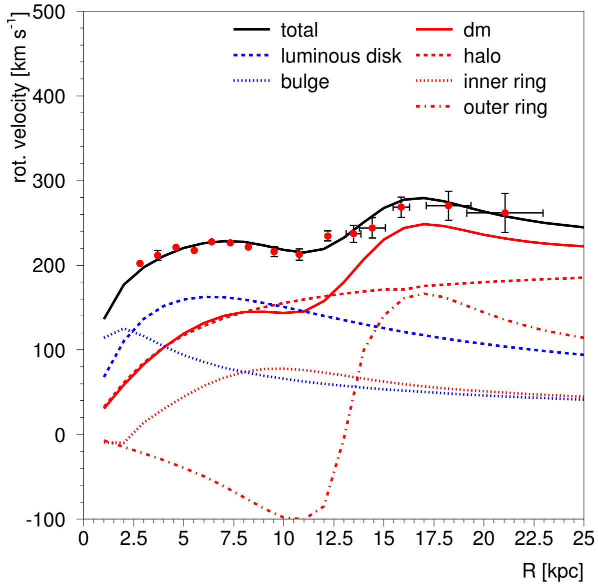

Figure 4. The rotation curve from our galaxy with the DM contribution determined from the EGRET excess of diffuse gamma rays. The data are averaged from Ref. (6).

(19; 20; 21). These stars show a much smaller velocity dispersion (10-30 km/s) and larger z-distribution than the thick disk, so they cannot be considered an extension of the disk. A viable alternative is the infall of a dwarf galaxy (19; 22), for which one expects in addition to the visible stars a DM component. From the size of the ring and its peak density one can estimate the amount of DM in the outer ring to be $\approx 10^{10} - 10^{11}$ solar masses. Since the gamma ray excess requires the full $360°$ of the sky, one can extrapolate the observed $100°$ of visible stars to obtain a total mass of $\approx 10^8 - 10^9$ solar masses (19; 20), so the baryonic matter in the outer ring is only a small fraction of its total mass.

The inner ring at 4.2 kpc with a width of 4.2 kpc in radius and 0.2 kpc perpendicular to the disk is more difficult to interpret, since the density of the inner region is modified by adiabatic compression and interactions between the bar and the halo. However, it is interesting to note that its radius coincide with the ring of cold dense molecular hydrogen gas, which reaches a maximum density at 4.5 kpc and with a width around 2 kpc (23; 14). Since molecular hydrogen forms in regions with dust (which provides shelter against dissociating UV radiation and allows atomic hydrogen to bond at the surfaces) suggests a gravitational potential well in this region, in agreement with the EGRET excess in this region.

To prove that the enhanced gamma ray density is indeed connected to non-baryonic mass the rotation curve was reconstructed from the excess of the diffuse gamma rays in the following way: since the flux determines the number density of DM for a given boost factor and since the mass of each WIMP is between 50 and 100 GeV, one can determine the relative masses of the components (rings plus spherical part) and consequently predict the shape of the rotation curve. The absolute value of the mass can be obtained by requiring that the rotation speed of the solar system is 220 km/s at 8.3 kpc. The two ring model describes the peculiar change of slope at 11 kpc well, as shown in Fig. 4. The contributions from each of the mass terms have been shown separately. The basic explanation for the negative contribution from the outer ring is that a tracer star at the inside of the ring at 14 kpc feels an outward force from the ring, thus a negative contribution to the rotation velocity.

3. Objections to the DMA interpretation

The DMA interpretation of the EGRET excess would mean that DM is not so dark anymore, but DM is visible from the 30-40 flashes of energetic gamma rays for each annihilation. This would be great, but are there more mundane explanations? Attempts to modify the electron and proton spectra from the locally measured spectra do not describe the shape of the EGRET data in all sky directions, as discussed in detail before by comparing the EGRET data with the “optimized model”. Here we summarize some other possible objections.

a) Are the EGRET data reliable enough to make such strong conclusions? The EGRET detector was calibrated in a quasi mono-energetic gamma ray beam at an accelerator, so its response is well known. Also the monitoring during the flight was done carefully. We have only used data in the energy range between 0.1 and 10 GeV, where the efficiency is more or less flat. So we believe the 9 years flight provided accurate and reliable data, especially it would be hard to believe in an undetected calibration problem, which would only effect the data above 0.5 GeV and fake the gamma ray spectrum from the fragmentation of mono-energetic quarks.

b) Is it possible to explain the excess in diffuse gamma rays with unresolved point sources? This is unlikely, first of all since the known point sources are only a small fraction of the diffuse gamma rays and the majority of the resolved sources has a rather soft spectrum, typically well below 1 GeV, as can be seen from the plots in the Appendix. If this part of the spectrum would be dominated by unresolved sources, then the diffuse component below 1 GeV would be lower than assumed, which in turn would lead to a lower normalization of the background and a correspondingly stronger excess for a fixed background shape. So arguing against DMA by unresolved sources goes in the wrong direction.

c) The tracing of DM relies largely on the outer rotation curve of our galaxy, which has large uncertainties from the distance r_0 between the Sun and the galactic centre and is determined with a different method than the inner rotation curve. Can this fake the results? The outer rotation curve indeed depends strongly on r_0, as shown in Ref. (24), who varied r_0 between 7 and 8.5 kpc. At present one knows from the kinematics of the stars near the black hole at the centre of our galaxy that $r_0 = 8 \pm 0.4$ kpc (25), so the distance is already reasonably well known. But whatever the value of r_0, the change in slope around $1.3r_0$ is always present, indicating a ringlike DM structure is always needed. Furthermore the outer rotation curve shows first the same decrease as the inner rotation curve and only then changes the slope, so the different methods agree.

d) The outer ring at 14 kpc has a mass between 10^{10} and 10^{11} solar masses. This is around 30-50% of the total mass inside the ring and one may worry about the disk stability of the Milky Way by the infall of such a heavy galaxy. However, large spiral galaxies show bumps of similar size (26), so it seems not to be uncommon to have masses of this size forming ringlike structures. Note that only ringlike structures can form maxima and minima in the outer rotation curve, since the rotation velocity squared is proportional to the *derivative* of the gravitational potential.

e) One observes a ring of molecular hydrogen near the inner ring and a ring of atomic hydrogen near the outer ring. Could this excess of hydrogen not be responsible for the excess of the gamma rays? No, our method of fitting only the shapes with a free normalization implies that this analysis is insensitive to density fluctuations of the background, which change the normalization, not the shape.

f) How can one be sure that the outer ring originated from the tidal disruption of a rather massive satellite galaxy, so one can expect an enhanced DM density in the ring? One finds three independent ringlike structures: stars, atomic hydrogen gas and excess of gamma radiation. The stars show a scale height of several kpc and a low velocity dispersion, so they cannot be part of the galactic disk. Therefore the infall of a satellite galaxy is the natural explanation. Since the tidal forces are proportional to $1/r^3$, the satellite will be disrupted most strongly at its pericentre, leaving behind gas, stars and DM. All three are found with more than 90% of the mass being DM.

g) Is it not peculiar that if a ringlike structure originates from the infall of dwarf galaxy, that it lies in the plane of the disk? In principle the infall can happen in all directions with respect to the plane, but the angular momenta of the inner halo and a baryonic disk tend to align after a certain time by tidal torques (27).

4. Summary

In summary, the EGRET data shows an intriguing hint of DM annihilation, since it explains many unrelated facts simultaneously:

a) An excess of diffuse galactic gamma rays which shows a *spectrum* consistent with the expectation from WIMP annihilation into gamma rays originating from the fragmentation of mono-energetic quarks.

b) The excess is present in *all* sky directions with the same spectrum, thus excluding that it originates from anomalous contributions in the centre of the galaxy.

c) The excess shows an strongly increased intensity at positions where extra DM is expected, namely at two toroidal structures at radii of 14 and 4 kpc from the centre of the galaxy. At 14 kpc one has observed a ring of stars thought to originate from the infall of a dwarf galaxy, while at 4 kpc one finds an enhanced concentration of molecular hydrogen thought to form from atomic hydrogen in the presence of dust or heavy nuclei, which can be collected in the gravitational potential of a ring of DM.

d) The mass in the rings can be obtained from the flux of the excess and describes the hitherto mysterious change of slope in the rotation curve at a distance of about 11 kpc, thus proving that the EGRET excess traces the Dark Matter.

In our analysis we only fit the known spectral shapes of the various processes with arbitrary normalizations, so the analysis becomes largely model independent. Interestingly, the normalization factors come out to be in agreement with expectations, both for the WIMP signal and the background.

The statistical significance of the EGRET excess of at least 10 σ, if fitted to the shape of the conventional diffuse gamma ray background only, combined with all features mentioned above provides an intriguing hint that this excess is indeed indirect evidence for Dark Matter annihilation. The fact that we can calculate the peculiar shape of the rotation curve of our galaxy from the gamma rays proves that the excess indeed traces the Dark Matter.

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