The dark connection between the Canis Major dwarf, the Monoceros ring, the gas flaring, the rotation curve and the EGRET excess of diffuse Galactic Gamma Rays

W. de Boer, I. Gebauer, M. Weber, C. Sander, V. Zhukov[1] [a] and D. Kazakov[2]

[1] Institut für Experimentelle Kernphysik, University of Karlsruhe, Postfach 6980, 76128 Karlsruhe, Germany
[2] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia

Abstract. The excess of diffuse galactic gamma rays above 1 GeV, as observed by the EGRET telescope on the NASA Compton Gamma Ray Observatory, shows all the key features from Dark Matter (DM) annihilation: (i) the energy spectrum of the excess is the same in all sky directions and is consistent with the gamma rays expected for the annihilation of WIMPs with a mass between 50-100 GeV; (ii) the intensity distribution of the excess in the sky is used to determine the halo profile, which was found to correspond to the usual profile from N-body simulations with additional substructure in the form of two doughnut-shaped structures at radii of 4 and 13 kpc; (iii) recent N-body simulations of the tidal disruption of the Canis Major dwarf galaxy show that it is a perfect progenitor of the ringlike Monoceros tidal stream of stars at 13 kpc with ring parameters in agreement with the EGRET data; (iiii) the mass of the outer ring is so large, that its gravitational effects influence both the gas flaring and the rotation curve of the Milky Way. Both effects are clearly observed in agreement with the DMA interpretation of the EGRET excess.

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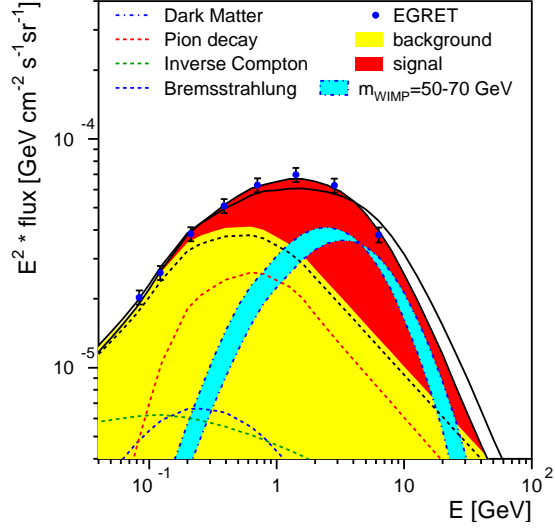
1 Introduction

If dark matter (DM) is created thermally during the Big Bang the present relic density is inversely proportional to $\langle \sigma v \rangle$, the annihilation cross section σ of DM particles, usually called WIMPS (Weakly Interacting Massive Particles), times their relative velocity. The average is taken over these velocities. This inverse proportionality is obvious, if one considers that a higher annihilation rate, given by $\langle \sigma v \rangle n_\chi$, would have reduced the relic density before freeze-out, i.e. the time, when the expansion rate of the Universe, given by the Hubble constant, became equal to or larger than the annihilation rate. For the present value of $\Omega h^2 = 0.105 \pm 0.008$, as measured by WMAP [1], the thermally averaged total cross section at the freeze-out temperature of $m_\chi/22$ must have been around $3 \cdot 10^{-26}$ cm^{3}s^{-1} [2]. If the s-wave annihilation is dominant, as expected in many supersymmetric models, then the annihilation cross section is energy independent, i.e. the cross section given above is also valid for the cold temperatures of the present universe [5]. Such a large cross section will lead to a production rate of mono-energetic quarks[1] in our Galaxy, which is 40 orders of magnitude above the rate produced at any accelerator. The fragmentation of these quarks will lead to a large flux of gamma rays with a characteristic energy spectrum quite different from the background of cosmic ray interactions with the interstellar material of the Galaxy. In addition, gamma rays have the advantage that they point back to the source and do not suffer energy losses, so they are the ideal candidates to trace the dark matter density. The charged components interact with Galactic matter and are deflected by the Galactic magnetic fields, so they do not point back to the source. Therefore the charged particle fluxes have large uncertainties from the propagation models, which determine how many of the produced particles arrive at the detector. For gamma rays the propagation is straightforward: only the ones pointing towards the detector will be observed.

An excess of diffuse gamma rays compatible with dark matter annihilation (DMA) has indeed been observed by the EGRET telescope on board of NASA's CGRO (Compton Gamma Ray Observatory)[4]. The excess was observed in all sky directions, which would imply that DM is not dark anymore, but shining in gamma rays. Of course, such an important observation needs to be scrutinized heavily. Before discussing the criticism the evidence and new confirmation from N-body simulations and the gas flaring is presented in the next section.

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[a] *Email:* wim.de.boer@cern.ch

[1] The quarks are mono-energetic, since the kinetic energy of the cold dark matter particles is expected to be negligible with the mass of the particles, so the energy of the quarks equals the mass of the WIMP.
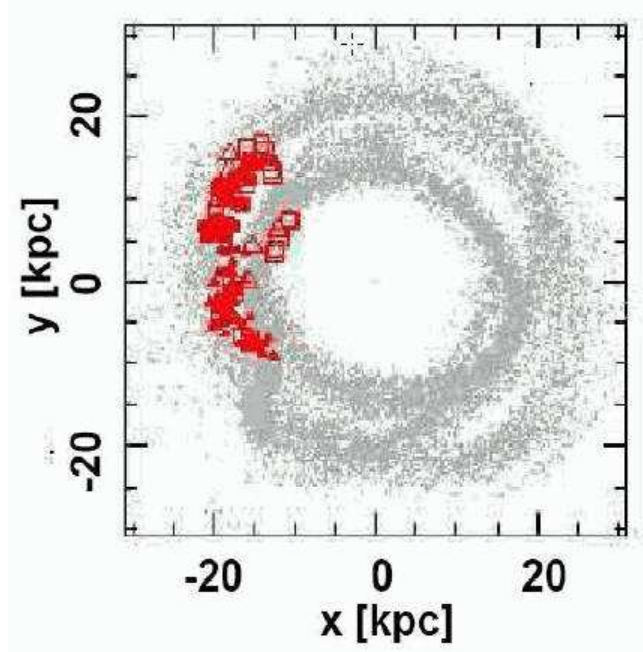
Fig. 1. Fit of the shapes of background and DMA signal to the EGRET data in the direction of the Galactic centre The light shaded (yellow) area indicates the background using the shapes known from accelerator experiments, while the dark shaded (red) area corresponds to the signal contribution from DMA for a 60 GeV WIMP mass. The intermediate (blue) shaded area corresponds to a variation of the WIMP mass between 50 and 70 GeV.

Fig. 2. Results of an N-body simulation of the tidal disruption of the Canis Major dwarf Galaxy, whose orbit was fitted to the observed stars (red points). The simulation predicts a ringlike structure of dark matter with a radius of 13 kpc. From [14].

2 The DMA interpretation of the EGRET excess of diffuse Galactic gamma rays

The EGRET excess on diffuse gamma rays was first observed by Hunter et al. in 1997 [3]. Below 1 GeV the CR interactions describe the data perfectly well, but above 1 GeV the data are up to a factor two above the expected background. The excess shows all the features of DMA annihilation for a WIMP mass between 50 and 70 GeV [4]. Especially, the two basic constraints expected from any indirect DMA signal are fulfilled: (i) the excess should have the same *spectral shape* in all sky directions. (ii) the excess should be observable in a large fraction of the sky with an *intensity distribution* corresponding to the gravitational potential of our Galaxy. The latter means that one should be able to relate the distribution of the excess to the rotation curve. Both conditions, which form a formidable constraint, are met by the EGRET data [4]. In addition, the results are perfectly consistent with the expectations from Supersymmetry[5,6].
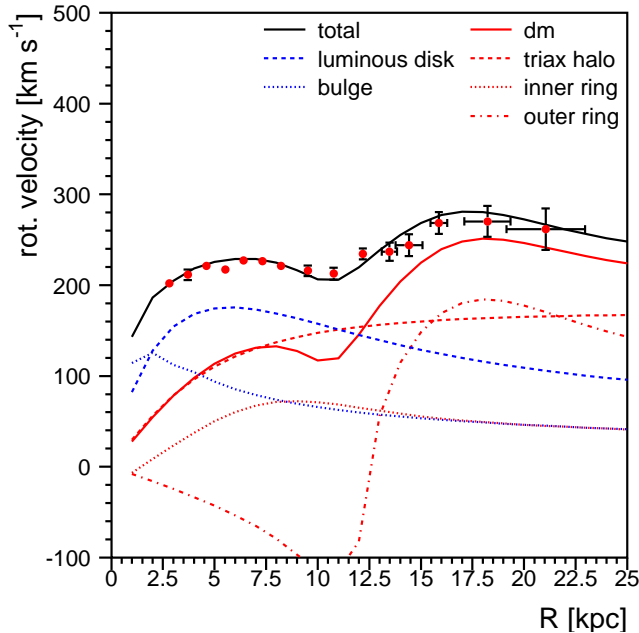
The analysis of the EGRET data is simplified by the fact that the spectral shapes of the DMA contribution and the background from CR interactions with the gas of the disk are well known from accelerator experiments: (i) the DMA signal should have the gamma ray spectrum from the fragmentation of mono-energetic quarks, which has been studied in great detail at LEP. (ii) the background in the energy range of interest is dominated by cosmic ray (CR) protons hitting the hydrogen of the disk. Therefore the dominant background spectral shape is known from fixed-target experiments. Given that these shapes are known from the two best studied reactions in accelerator experiments allows to fit these *known* shapes to the observed

gamma ray spectrum in a given sky direction and obtain from the fitted normalization constants the contribution of both, background and annihilation signal. So in this case one does not need propagation models to estimate the background, since the data itself calibrates the amount of background. In addition, fitting the shapes eliminates the uncertainties from the overall normalization error in the data and only the reduced point-to-point errors have to be taken into account. A typical gamma ray energy spectrum is shown in Fig. 1, which clearly shows the rather distinct spectral shapes for DMA and background, so the two normalization constants of DMA and background are not strongly correlated. The blue area corresponds to the difference in WIMP mass between 50 and 70 GeV. The latter gives already a considerably worse fit, since the total flux is too low near the maximum and too high for the highest bin, so the range 50-70 GeV is the preferred WIMP mass. The DM halo, as determined from the dark matter normalization factors in 180 independent sky directions, shows doughnut-like structures at 4 and 13 kpc [4]. More details can be found in the contribution to these proceedings[7]. The ring at 4 kpc (inner ring) coincides with the ring of dust in this region. The dust is presumably kept there because of a gravitational potential well, which is provided by the ring of DM. The ring at 13 kpc (outer ring) is thought to originate from the tidal disruption of the Canis Major dwarf galaxy, which circles the Galaxy in an almost circular orbit coplanar with the disk [8,9]. Three independent observations confirm this picture of the ring originating from the tidal disruption of a dwarf galaxy:
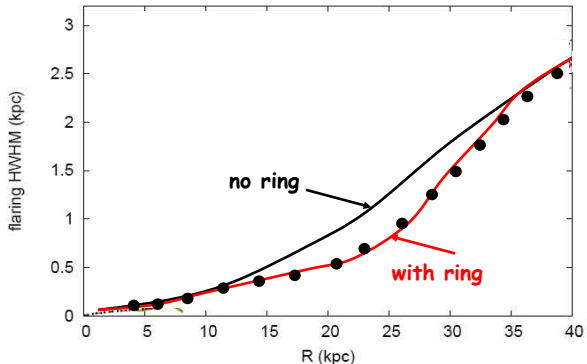
(i)a ring of DM is expected in this region from the observed ring of stars, called Monoceros ring, which

Fig. 3. The rotation curve with the contributions of the bulge, the disk, the triaxial dark matter halo and the two ringlike structures. The outer ring causes the peculiar change of slope in the rotation curve at about 11 kpc. From [4].

Fig. 4. The half-width-half-maximum (HWHM) of the gas layer of the Galactic Disk as function of the distance from the Galactic center. Clearly, the fit including a ring of dark matter above 10 kpc describes the data much better. Adapted from data in [16].

was discovered first with SDSS data [10,11]. Follow-up observations [12] found that this structure surrounds the Galactic disk as a giant ring (observed over 100 degrees in latitude) at Galactocentric distances from 8 kpc to 20 kpc. Tracing this structure with 2MASS M giant stars, [13] suggested that this structure might result from the tidal disruption of a merging dwarf galaxy. N-body simulations show indeed that the overdensity in Canis Major is indeed a perfect progenitor for the Monoceros stream and they predict a DM ring at 13 kpc with a low ellipticity and almost coplanar with the disk, as shown in Fig. 2 (from Ref. [14]). The orientation of the major axis at an angle of 20 degrees with respect to the axis sun-Galactic centre and the ratio of minor to major axis around 0.8 agree with the EGRET ring parameters given in Ref. [4]. This correlation with the EGRET excess lends both support to the DMA interpretation of the EGRET excess, the connection between the Monoceros stream and the Canis Major dwarf galaxy and its outer galactic origin. The overdensity of stars forming the Canis Major dwarf is sometimes defended as being a warp of the Galactic disk (see discussions e.g. in [15]).

(ii) Such a massive ring structure influences the rotation curve in a peculiar way: it decreases the rotation curve at radii inside the ring and increases it outside. This is apparent from the change in direction of the gravitational force from the ring on a tracer, since this force decreases the force from the galactic centre for a tracer inside the ring, but increases it outside the ring. This is indeed observed as shown in Fig. 3, where the

negative contribution of the outer ring is clearly visible.

(iii) A direct proof of the large amount of DM mass in the outer ring comes from a recent analysis of the gas flaring in our Galaxy [16]. Using the new data of the LAB survey of the 21 cm line in our Galaxy led to a precise measurement of the gas layer thickness up to radii of 40 kpc. The increase of the half width of the layer after a decrease to half its maximum value (HWHM) as function of distance is governed by the decrease in gravitational potential of the disk. The outer ring increases the gravitational potential above 10 kpc, which is expected to reduce the gas flaring. Only after taking the ring like structure into account the reduced gas flaring in this region could be understood. The effect is shown in Fig. 4. A fit averaged over all longitudes requires a DM ring with a mass of $2 \cdot 10^{10}$ solar masses, in rough agreement with the EGRET excess.

Clearly, these three independent astronomical observations need a ringlike DM structure above 10 kpc, thus providing independent evidence for the DMA interpretation of the EGRET excess.

3 Alternatives to the DMA interpretation of the EGRET excess and criticism

Alternative models for the EGRET excess without DM have to assume that the locally measured fluxes of protons and electrons are not representative for our galaxy [17]. In this case the cosmic ray spectrum of protons and electrons is not taken to be the locally observed one, but modified to increase the gamma ray spectrum at high energies. This requires a strong break in the injection spectrum of electrons and protons in order not to change the gamma ray spectrum below 1 GeV, but only above 1 GeV. Such a change in the shape of the spectrum is unexpected, since the fast diffusion as compared to the energy loss time equalizes the spec-

trum everywhere in the Galaxy, in agreement with the fact that the spectrum in all directions is observed to be the same.

Another explanation is provided by tuning the efficiency of the EGRET spectrometer to simulate DMA [18]. However, this requires the efficiency already to be modified around 1 GeV and reaching a change in efficiency of 100% at 10 GeV in clear disagreement with the calibration error in a photon beam before launch[19] and the residual uncertainties below 20% during the flight after correcting for time dependent effects[20]. Although there is some uncertainty in the efficiency of the veto counter at higher energies because of the backsplash from the calorimeter, this effect should not start at 1 GeV. Even if the errors are larger than estimated, it would be a remarkable coincidence that the excess corresponds exactly to the very specific sharply falling spectrum from the fragmentation of mono-energetic quarks! Furthermore, if one only fits the shape of the gamma ray spectrum all common normalization errors cancel, so one is only sensitive to the relative point-to-point errors in the data, which are considerably smaller.

Among the most important criticism was a paper by [21] claiming that the antiproton flux from DMA, using the DM distribution from the EGRET excess, would be an order of magnitude higher than the observed antiproton flux. They used a simple propagation model assuming the propagation of charged particles to be the same in the halo and the disk. Such common propagation models describe all present data, but this is *no* guarantee that they represent the truth, since the data is observed locally and inferring the propagation in the whole Galaxy from local data does not have a unique solution. E.g. Galactic wind models have anisotropic propagation, not only because of the convection, but also because the diffusion in the halo is expected to be much faster than in the disk [22].

Such an anisotropic diffusion model leads to a strong reduction of the antiproton flux from DMA, since the antiprotons are preferentially produced in the halo and stay there or move to outer space instead of diffusing randomly. Therefore, instead of rejecting the DMA interpretation of the EGRET excess by models based on isotropic diffusion without regular magnetic fields, DMA can be used as an opportunity to construct an anisotropic propagation model. It is shown in a separate contribution to this conference that such a model can simultaneously describe the EGRET excess, the antiproton flux and the production of secondaries, if DMA is introduced as a source term in the model [23].

In summary, the gamma rays play a very special role for indirect DM detection, since they point back to the source. Therefore the gamma rays provide a perfect means to reconstruct the dark matter halo by observing the intensity of the gamma ray emissions in the various sky directions. The halo profile can in turn be used to calculate the shape of the rotation curve. Fitting the background and DMA shapes to the data in 180 independent sky directions reveals indeed a WIMP mass around 60 GeV in all sky directions and a halo profile with substructure consistent with the rotation curve, N-body simulations and the gas

flaring. For the halo profile one is only interested in the relative contributions in the various sky directions, so here all experimental errors largely cancel, since the EGRET satellite does not care in which direction it measures.

Therefore we consider DMA is a viable explanation of the EGRET excess of diffuse Galactic gamma rays, especially since it is observed with the same shape of the fragmentation of mono-energetic quarks in all sky directions and the intensity distribution of the excess traces the DM profile, as shown independently by the rotation curve, the gas flaring and the N-body simulation of the disruption of the Canis-Major satellite galaxy.

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