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Evidence for a Galactic γ-ray halo

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ABSTRACT

We present quantitative statistical evidence for a γ-ray emission halo surrounding the Galaxy. Maps of the emission are derived. EGRET data were analyzed in a wavelet-based non-parametric hypothesis testing framework, using a model of expected diffuse (Galactic + isotropic) emission as a null hypothesis. The results show a statistically significant large scale halo surrounding the center of the Milky Way as seen from Earth. The halo flux at high latitudes is somewhat smaller than the isotropic γ-ray flux at the same energy, though of the same order ($O(10^{-7}$–$10^{-6})$ ph cm^{-2} s^{-1} sr^{-1} above 1 GeV).

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1. Introduction

The study of diffuse high-energy γ-ray emission has proceeded along two complementary paths. The first is via the use of parametric methods (see e.g. Hunter *et al.* 1997), where a physically motivated model described by a small number of parameters is fit to the data. The alternate approach (see e.g. Chen, Dwyer, and Kaaret 1996 and Willis 1996) is non-parametric, where one attempts to find the flux distribution as a function of position without reference to a particular model. The two classes complement each other in the sense that the strengths of one are often the weaknesses of the other. For instance, while a parametric fit usually gives some global measure of how good the fit is, but does not tell you where the model fails (e.g., "the model did not account for this blob of flux over there"). The non-parametric approach can give this information, but unlike the parametric analysis, the quantitative assessment of the results is complicated by the effects of statistical bias. This latter point should be born in mind when examining the results presented in this paper.

Non-parametric analysis of photon-limited data is beset by certain difficulties, key of which is that Poisson noise is neither stationary nor additive. Thus, the results of what would be a straight-forward analysis (e.g. smoothing by a Gaussian kernel) for data contaminated by white noise are more difficult to interpret. We therefore apply a new wavelet-based technique which has the following characteristics:

- Rigorous treatment of Poisson statistics.

- Assessment (in some sense) of the statistical significance of the results.

- Spatial adaptivity, in that structures at different size scales are recovered automatically.

In this paper we apply non-parametric analysis to EGRET data taken during Phases 1-4 of the Compton Gamma Ray Observatory (CGRO) mission. Below we describe the non-parametric analysis method, and present results from EGRET data showing an extended halo of γ-ray emission apparently surrounding the center of the Milky Way. We show that this halo is statistically very strong in the data, and not obviously attributable to any systematic effect of the analysis or instrument, from which we conclude that it is most likely of astrophysical origin. We conclude with some brief discussion on the possible origins and implications of the γ-ray halo. This work expands upon that first presented in Dixon *et al.* 1997 and Dixon *et al.* 1998.

2. Basics of the Method

The non-parametric framework is a variant of the TIPSH (Translationally Invariant Poisson Smoothing using Haar wavelets) methodology, first introduced for denoising γ-ray burst light curves (Kolaczyk 1996,Kolaczyk 1997). A detailed description of the approach is described in a forthcoming paper (Kolaczyk and Dixon 1998); we give a brief outline here.

The goal of TIPSH is as follows: given a dataset consisting of observed counts per pixel, estimate the *expected* counts per pixel over the image. In essence, we accomplish this by assuming that the photon intensity distribution which generates the data contains local spatial correlations, and that there are multiple length scales associated with these correlations. That is, the pixel-to-pixel variations in the underlying photon intensity distribution are not random, but rather have some structure related to the physics governing the emission. *Wavelets* form bases for the space of square-integrable functions, and are explicitly constructed to compactly encode such correlated multiscale information. We therefore expect that wavelets will be useful for extracting the coherent information in favor of the random noise. This expectation is borne out by a large body of work (see, e.g., Donoho 1995). In addition, wavelet transforms can be accomplished via

fast algorithms, which allow them to be realistically applied to larger datasets.

As implied by the name, TIPSH utilizes Haar wavelets. These are the simplest of all wavelets, simply taking the value $+1$ or -1 over the region of non-zero support; 2D examples are shown in Figure 1. The Haar transform of an image provides a set of coefficients, one of which is simply the average intensity, with the others providing information about the intensity variation over different size scales in the horizontal, vertical, and diagonal directions. The particular form of the Haar wavelet makes it conducive to analysis of Poisson data. The sum of counts over pixels is simply a Poisson variable, and thus (excepting the DC level) the Haar coefficients are distributed as the *difference* between two Poisson distributed random variables. This, coupled with the statistical independence of the coefficients within a given size scale and direction (the wavelets have no overlap), allow us to derive convenient expressions for the statistical distribution of wavelet coefficients (see Kolaczyk and Dixon 1998 for more details). We can then use these to calculate the probability that a coefficient of the observed size or larger is statistically consistent with some null hypothesis.

TIPSH is a "keep-or-kill" strategy, applied to the Haar coefficients of the difference between the data and some hypothesized count distribution, i.e., an estimate of the background or "known" emission. If the magnitude of the coefficient exceeds some threshhold, it is kept, otherwise it is zeroed out. After application of this procedure, the inverse Haar transform is applied to the remaining coefficients, giving the estimated denoised residual count distribution. Except for the case of a constant background, simple expressions for the keep-or-kill threshholds are not available. We instead exploit the following property: given threshhold t, and an observed value h^{obs} of wavelet coefficient h,

$$h^{\text{obs}} > t \quad \text{if and only if} \quad \Pr(h > h^{\text{obs}}) < \Pr(h > t) \; . \tag{1}$$

Calculation of these probabilities (known as *p-values*) requires the specification of a Poisson distribution under some null hypothesis or "background". We supply a count distribution which serves as the null hypothesis. We then need a way of specifying the p-value cutoff corresponding to a "significant" detection. For this paper, we use the level-wise false detection rate (FDR), which is simply the probability that one or more wavelet coefficients in a given resolution and direction would accidentally be deemed significant if the null hypothesis reflected the actual intensity distribution underlying the data. The wavelet coefficients within a given size scale and direction (horizontal, vertical, diagonal) are statistically independent, as they have no spatial overlap. The coefficient-wise FDR α_k for the kth coefficient is thus simply calculated from the expression

$$\text{FDR} = 1 - (1 - \alpha_k)^n, \tag{2}$$

where n is the number of coefficients for a particular size scale. We calculate $\Pr(h_k > h_j^{obs})$ via an algorithm due to Posten (Posten 1989), use the relation $\Pr(h_k > t) = \alpha_k/2$, and apply eqn. 1 to decide if we keep coefficient k.

Finally, we note that the analysis is carried out in the translationally invariant or "cycle spinning" (Donoho and Coifman 1995) framework. The main reason for this is that the Haar wavelets themselves are not smooth functions, while we expect a somewhat higher degree of regularity in the estimated intensity distribution. More specifically, the Haar function is piecewise constant and (in the continuum limit) non-differentiable. Astrophysical intensity distributions, however, are likely "smoother" in the sense of being locally approximated by higher order polynomials. The compression property of the wavelet transform is directly related to this. Wavelets are often explicitly constructed to be orthogonal to polynomials up to some given order. As such, regions in a signal which are closely approximated by polynomials of that order or smaller will yield small wavelet coefficients.

The Haar wavelet is the lowest order wavelet in this sense, being orthogonal only to the constant function. Though the (discrete) Haar basis can be used to represent *any* (discrete) measured image or intensity distribution, some information is spent to "smooth out the corners", i.e., to fill in any higher order smoothness. The threshholding procedure is likely to wipe out some of that information, resulting in pseudo-Gibbs artifacts reflecting the "blocky" appearance of the Haar wavelets. While going to a higher order wavelet nominally solves this problem, in this case adjacent wavelets would have spatial overlap, and so their coefficients would no longer be statistically independent. Further, the wavelet coefficients in this case are constructed from non-trivial weightings of measured counts, and as such the corresponding p-values are much more difficult to calculate. So the use of Haar wavelets is necessary to maintain the rigor and simplicity of our approach.

To mitigate the functional/approximation shortcomings of Haar wavelets, we instead effectively perform the analysis over all horizontal and vertical shifts of the data, and average together these results to obtain the final estimate. In actuality, much of the information in such a procedure is redundant, and so we can obtain the requisite information via an $O(N \log N)$ algorithm. Without going into the mathematical details (see Donoho and Coifman 1995 for a discussion), the average-over-shifts procedure yields gains in both the continuity and approximation order of the estimate when compared with the classical Haar basis. An analogous astronomical procedure is that of *dithering*, where multiple observations of the same region are taken while moving the telescope by an amount smaller than the angular size of a CCD (or other) pixel. We emphasize that statements about detection rates, etc., apply only *within* a given shift.

3.   Details of the Analysis

The data analyzed and discussed below are for $E > 1$ GeV, from Phases 1–4 of the CGRO mission. For completeness, we shall later present results for the energy ranges $100 < E < 300$ MeV and $300 < E < 1000$ MeV, but our discussion here will concentrate above 1 GeV. Analysis is performed directly on the photon data, binned in $0.5° \times 0.5°$ pixels. The wavelet transform is most easily implemented for datasets of size 2^J, where J is some integer. The nominal all-sky EGRET dataset is 720×360 pixels. To achieve the proper size, we pad the 720×360 data to a size of 1024×1024 using segments of the data to achieve spherical boundary conditions. This implies that the data are periodic in longitude, while the pixels at the poles are aligned with their counterparts 180 degrees away. In this way the proper symmetries of the celestial sphere are enforced, reducing the possibility for artifacts due to artificial discontinuities at the data boundaries. Similar padding was performed on the null hypothesis, described below.

The null hypothesis consists of the sum of two components. The first is uniform in flux, accounting for the isotropic γ-ray background, and is included at a level computed from the spectrum of Sreekumar *et al.* 1998. The second component is standard Galactic diffuse model used in EGRET likelihood analysis, which is publicly available from the Compton Observatory Science Support Center (COSSC); this model is shown in Figure 2. This model is similar to that described by Bertsch *et al.* 1993 and Hunter *et al.* 1997, and describes γ-ray emission due to cosmic-ray interactions with interstellar matter and low-energy photons via the processes of bremsstrahlung, inverse Compton scattering, and nuclear processes ($pp \rightarrow \pi^{\pm,0}, \pi^0 \rightarrow \gamma\gamma$). The predicted γ-ray intensity is computed from line-of-sight integrals for these processes, based on an estimate of the three-dimensional distribution of Galactic matter, some cosmic-ray in-

jection spectra, and the assumption that the cosmic-ray source density is (at least on large scales) closely correlated with the distribution of matter. The diffuse model obtained from COSSC has been convolved with the approximate EGRET PSF for a given energy band. The predicted count distribution is given by the sum of the Galactic and isotropic components multiplied by the composite exposure factor of Phases 1–4.

Each 1024×1024 padded dataset was processed by TIPSH, using the null hypothesis described above and a variety of FDR's. Maps were generated for FDR's ranging from 10^{-2} to 10^{-15}, and though the map details changed (the map becomes smoother as the FDR is decreased), the basic result we present in this paper was essentially unchanged. Remember that the FDR we use applies to an entire resolution level and particular shift and direction, and gives the probability that if the null hypothesis were true, we would keep one or more wavelet coefficients due solely to Poisson fluctuations in the data. Reference to eqn. 2 shows then that the coefficient-wise FDRs α_k are going to be considerably smaller than the level-wise FDR. The particular level-wise FDR used for the figures is 10^{-4}. One can envision other choices for the level-wise (or coefficient-wise) FDRs; the choice of a single level-wise FDR is easy to implement and makes for straightforward interpretation.

4. Results and Consistency Checks

The TIPSH residual relative to the standard diffuse prediction is shown in Figure 3. This shows the all-sky map for $E > 1$ GeV generated by the processing described above. For clarity, we have separated the positive and negative components of the residual. The positive residual map shows several localized excesses corresponding to known point sources, as well as a general excess in the Galactic plane which is discussed in Hunter *et al.* 1997. Further, we can clearly see what appears to be a large scale emis-

sion halo surrounding the Galaxy. The negative residual map shows only a few artifacts related to point sources; these are expected since wavelets, while providing an excellent representation of extended spatially-correlated structure, perform rather poorly for isolated localized structures such as point sources.

The presence of point sources in the residual is expected, since we did not account for the point sources in our hypothesis. The plane excess is also expected, as it is known that the spectral distribution of the standard Galactic diffuse model underpredicts what is observed above 1 GeV. Hunter *et al.* 1997 states (for a slightly different version of this model) that the Galactic plane emission is actually 60% greater than that predicted. Pohl 1998 gives a figure of a 40% excess over the whole sky, and further claims that a simple scaling of the standard model will account for the excess.

To better understand which parts of the residual can be accounted for by such scaling and which represent a truly different spatial distribution of flux, we reanalyze the data using hypotheses where the Galactic diffuse contribution has been scaled up by some factor. The result for a 40% increase is shown in Figure 4. From the largely negative regions along the plane, we see that the contribution from the standard model distribution has been overestimated in this case. Yet high latitude excess is still apparent about GC, indicating another component whose spatial distribution is *not* correlated with the model. Figure 5 shows the result for a scaling of 20%. Here we see little systematic excess or deficit along the plane, with much of the high latitude emission away from GC also having been removed. However, a large-scale feature centered at GC is still clearly evident. Our claim is that this feature cannot be made consistent with the spatial distribution predicted by the standard diffuse model. Since the 20% scaling best isolates the anomalous halo component, we shall refer to this result in what follows.

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The flux levels shown in Figure 5 are in the range 10^{-7}–10^{-6} ph cm^{-2} s^{-1} sr^{-1}. We shall further discuss below the various potential systematic errors in this estimate, and here simply note that at least as regards the large-scale structure, the flux estimate is probably good to a factor of two, if one neglects regions of low exposure. Unfortunately, estimates of statistical errors are generally difficult to obtain for non-parametric analyses, and this is the case here as well. We can avoid some of the difficulties related to exposure systematics by directly examining the counts. Of the ~85000 counts in the dataset, ~71000 are accounted for by the null hypothesis, including the 20% scaling of the Galactic diffuse model. From the GeV source catalog of Lamb and Macomb 1997 (which uses data similar to what we have employed), we estimate the total point source contribution to be about 7100 photons, leaving about 7400 in the rest of the residual, which appears to be primarily associated with the halo.

The immediate question arises as to the statistical significance of this feature. Though we are able to make rigorous statements about the coefficient-wise and level-wise FDR, similar quantification of object-wise significance (e.g., "this blob is significant at the $n\sigma$ level") are difficult. The main reason for this is that a given object, such as the halo, is most likely composed of many wavelets which are not statistically independent, and at this point, estimates of object-wise error rates appear to be mathematically intractable. However, while we can't assign a number to it, we can argue that the feature is quite significant. First, we may examine how many wavelets were found to be inconsistent with the null hypothesis, and compare this with our expectation for statistical fluctuations. Results are shown in Table 1. Our expectation is that if the null hypothesis were accurate, only 0.01% of the time would we accidentally detect a wavelet as significant due to noise. A large scale structure such as the halo is clearly composed mostly of large wavelets, and we find that the actual detection rates for the

large scale wavelets greatly exceed the expected rate for noise. Second, the halo persists even at a FDR of 10^{-15}, while most other features (such as point sources) are removed at such a severe threshhold. Remember that this measure of "significance" applies to the *wavelet* representation of the residual, and so we expect structures with a large degree of spatial correlation to survive harsher threshholding better than highly localized features (e.g., point sources). The opposite would be true if we were to perform threshholding directly on the pixel count values. Thus the halo clearly is a very strong effect in the data in terms of being a spatially coherent (albeit dim) structure.

The assessment of statistical significances is one of those areas which is difficult in non-parametric analyses, but quite straightforward in a parametric analysis. So we may also address the significance of the halo by fitting some model and examining the likelihood ratio when compared to a model that does not include a halo component. Clearly the exact result here is model dependent, but this approach at least gives us some handle on the statistics. For the case at hand, we fit a simple linear model:

$$\bar{d}_{ij} = E_{ij}(\alpha \cdot \text{ISO}_{ij} + \beta \cdot \text{GDM}_{ij} + \gamma \cdot \text{IC}_{ij}), \quad (3)$$

where the subscripts refer to the (i, j)th pixel, E is the exposure factor, ISO is the predicted isotropic background, GDM is the predicted Galactic diffuse model, and IC is a particular model of inverse Compton emission derived from a cosmic-ray propagation code (Strong and Moskalenko 1998). The distribution of IC is shown in Figure 6a, and while it may or may not reflect the "true" distribution of the halo, it at least gives us some component with approximately the right spatial characteristics. The parameters α, β, and γ are estimated by maximizing the Poisson likelihood. The null hypothesis for our likelihood ratio test simply omits the IC component. The full fit gives values $\alpha = 0.975$, $\beta = 1.3286$, and $\gamma = 0.5311$, while the fit to the null hypothe-

sis gives $\alpha = 1.2428$ and $\beta = 1.4352$. Following Mattox *et al.* 1996, we find a formal signficance of

$$\sqrt{TS} = \sqrt{2(\log L - \log L_0)} \simeq 21\sigma. \qquad (4)$$

Remember that this is the level at which the null hypothesis is *rejected* given the specific test we performed, and says nothing about how well the specific morphology of IC compares with some other morphology.

Processing by TIPSH gives an estimate of the average residual counts/pixel We then divide by the exposure to give the estimated flux over the region. This point merits some discussion. The total EGRET exposure is highly non-uniform on the sky, tending to be concentrated on sources of interest (see Figure 7). Thus, a spatially uniform flux signal yields a highly non-uniform count distribution in the data. TIPSH basically performs adaptive smoothing in count space, and though the algorithm is count conserving (w.r.t. the *total* counts in the dataset), details of the exposure pattern can get smoothed over, especially in areas of low exposure. Therefore we need to be careful in our interpretation of flux maps, in that we expect some anticorrelation of map features with the exposure pattern. These systematics generally also lead to distortion in the flux levels, so the contour levels shown in Figures 3, 5, and 4 should be taken with a grain of salt. Again, this effect is most pronounced in low exposure and/or low count regions. For comparison, Figure 8 shows the exposure overplotted on the residual flux map of Figure 5. Similarly, while TIPSH is count-preserving, the distortions due to the spatially non-uniform exposure imply that the total map flux is systematically off. We find that the total residual flux is usually overestimated, though generally only by a factor of two or so.

To better illustrate some of the statistical and systematic effects described above, we present some examples from simulated data. We begin showing the results of running TIPSH against a dataset generated directly from the null hy-

pothesis (Galactic diffuse + isotropic). Our expectation is that the level-wise FDR of 10^{-4} should effectively suppress the noise, with very few wavelets passing threshhold. This expectation is borne out by the actual detection rates in Table 1, as well as the residual shown in Figure 9.

Our second set of examples illustrates the level of systematic errors induced by non-uniform exposure effects. As we shall see, the spatially non-uniform exposure is the limiting factor in assessing morphology and flux levels. A simple way to see this effect is to add in excess isotropic signal, and examine the structure returned in the flux map. We thus simulate data with an isotropic component twice that which is measured, and use the same null hypothesis as above. Figure 10 shows the fractional deviation (given as (residual - isotropic)/isotropic) from the expected isotropic signal in the resultant residual flux map. As expected, we see anticorrelation with the exposure pattern (overplotted and also shown in Figure 7). Next we simulate data for with a 40% excess in the Galactic diffuse contribution. The input excess and TIPSH residual are shown in Figure 11. The level of distortion here is not so drastic, but again this might be expected since most of the excess is concentrated near the Galactic plane where the exposure tends to be relatively large. Figure 11b lends further credence to our argument that the halo is not simply an artifact of the standard model's underestimation of the observed flux above 1 GeV. Finally we simulate data where we include the IC model used in our parametric fit above, to see the effect of a more "halo-like" excess. Figure 6b shows the TIPSH residual. While there is some loss of small-scale information and obvious artifacts in regions of low exposure, we note that the contours corresponding to the broader components of the emission are not overwhelming displaced, particularly in the neighborhood of $l = 0°$. A similar conclusion might be drawn from Figure 12, which shows the ratio of the model to the recovered residual. This should not be

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too surprising, perhaps, since coefficients corresponding to large scale wavelets are derived from larger numbers of photons, and we thus expect them to be statistically more robust than their smaller scale counterparts.

The above discussion has largely concentrated on the spatial distribution of the halo above 1 GeV. We close this section by briefly touching on the spectral characteristics. Though we leave detailed analysis of the energy dependence to a future paper, we show the TIPSH results for 100-300 MeV and 300-1000 MeV in Figures 13 and 14 respectively. These are derived using the unscaled standard Galactic diffuse model and isotropic fluxes for these energy ranges derived from Sreekumar *et al.* 1998. Note that, unlike the case above 1 GeV, if anything the plane flux in these cases is *overestimated* by the model, and that the halo excess is still clearly present. It is tempting to simply read off fluxes from the various figures and construct a spectrum, but the discussion above certainly indicates that such an exercise should be undertaken with caution. Detailed spectral analysis necessarily requires a parametric approach, and we leave this for future research.

5. Discussion of potential systematics

Let us address some possible systematic non-astrophysical sources of the halo:

- *Exposure related*–From the discussion above, we do expect some artifacts due to the non-uniform exposure when the map is converted from counts to flux. However, the exposure variations occur on much smaller angular scales than that of the halo, and of course there's no artifacts without some excess flux in the first place. The examples from simulated data in the previous section certainly indicate that we are seeing a non-isotropic halo-like excess, albeit distorted by exposure artifacts. Another exposure related possibility might be expected from the threshholding behavior, in that more threshholding is going to occur in low-exposure regions, where there are less statistics. One might naively expect larger signal suppression in regions of lower exposure, as is sometimes seen, for example, with Maximum Entropy, resulting in apparent excess emission following the exposure map. Wavelets, however, have zero mean, so threshholding a particular wavelet does not change the total counts in the region encompassed by the wavelet support, but rather removes local structure variations at that scale (i.e., TIPSH is count-preserving). So, signal is not lost, but rather smeared out over a larger area in low-exposure areas, leading to the kind of smaller-scale artifacts discussed above. Examination of Figure 8 shows no obvious large-scale correlation of the halo and exposure; for example, the Galactic center and anticenter regions both have significant exposures, but the excess appears mostly about the Galactic center.

- *EGRET calibration errors*–It is known (Sreekumar *et al.* 1998) that the EGRET spark chamber efficiency varies over time, due to degradation in the gas, gas refills, etc. Calibration errors in the time-variable efficiency could conceivably lead to the appearance of apparently diffuse features. However, to generate what we see in Figure 5 would either require a very large error (on the order of 50% or greater) in calibrating a single observation near GC, or a systematic underestimation in the efficiency of most observations near GC, but nowhere else on the sky. Both of these options seem unlikely. Another systematic problem may come from the exposure at large detector zenith angles, which is not well quantified. The exposure at these large angles is small, and should not contribute much in a composite all-sky map. Further,

we have performed the same analysis on datasets with a 30° zenith cut, and again find that the large-scale results are essentially unchanged (additional small-scale artifacts appear due to the "hard edge" in the exposure caused by the zenith cut).

- *Errors in the point spread function*–Since we are denoising and not deconvolving, the point spread function (PSF) only enters into the analysis through the Galactic diffuse model, where the predicted γ-ray flux profile is convolved with the PSF to generate the expected intensity distribution in the data. The PSF used in this calculation is zenith averaged, so some small local deviations from the true PSF are likely. Such errors are probably not significant except for the brightest of sources, and certainly wouldn't generate the type of large-scale structure we see here. One could also posit a low-level spatially extended tail in the PSF. It is rather difficult to think of a physical cause for this (γ and $e^{\pm}$ scattering in the instrument are presumably well understood), and in this case the large-scale longitudinal smearing of Galactic plane emission would be considerably greater than what we see, which is of a rather more spherical appearance in Figure 5.

- *Oversmoothing of Galactic plane flux*–Denoising invariably requires some level of data smoothing, and so structures deemed significant by the algorithm generally appear somewhat smeared out, with the degree of smearing depending upon the statistical significance (less significant $\rightarrow$ more smeared). The locally adaptive nature of TIPSH should mitigate this effect a great deal, when compared with a non-adaptive method such as simply blurring the data with a Gaussian. Nonetheless, we should address the possibility that some fraction of the excess Galactic emission above 1 GeV is being

smoothed out to high latitudes, and giving the appearance of a halo. We can easily argue against this possibility by examining Figure 4. Here, we have a general *deficit* in the Galactic plane, but still detect a halo excess. Since all of the smoothing occurs in the residual, i.e., none is applied to the hypothesis, we would not see the halo without a plane excess if oversmoothing were the culprit.

- *Particle background*–While EGRET does use a charged particle anticoincidence shield, potential for proton-initiated background contamination does exist (see Sreekumar *et al.* 1998 for discussion). Further detailed study using Monte Carlo and examination of individual event track data is necessary to rule this out completely. However, we note that to date, there is no indication that cosmic-ray protons show such strong spatial anisotropy as seen here (see, e.g., Longair 1992). Further, the signal appears correlated with the Galaxy, as opposed to any particular orbital characteristics, and shows similar average properties as was seen in the COS-B result (Strong 1984). A non-γ-ray neutral particle signal seems even more unlikely.

- *Contamination by Earth albedo*–Rejection of Earth albedo is accomplished by making a cut on the reconstructed γ-ray arrival direction, based on the position of the Earth within the FOV. Due to the finite instrumental PSF, this approach is not perfect, and we expect some albedo contamination (Willis 1996). We emphasize that albedo contamination is largely a *local* effect, with the key question being the location of most of the contamination. Figure 3.6 of Willis 1996 shows a plot in celestial coordinates of those regions dominated by exposure to large ($\alpha > 80°$) Earth-limb zenith angles, for which it is expected that albedo con-

tamination will be most pronounced. We note that those regions with the largest expected albedo contamination are confined to the celestial polar regions, with $|dec| \geq 50°$. Curves delineating these regions on a Galactic plot are shown in Figure 15 overplotted on the residual flux map. While some parts of the halo do appear within these regions, most of it lays outside, and there is clearly no correlation between the halo distribution and the location and/or size of these areas. From this we conclude that the halo is not due to albedo contamination.

Ultimately, the only definitive statement we can make is that the halo is "in the data", statistically speaking. While γ-ray data is rather prone to contamination by systematic effects, given the above discussion and results, we feel the most likely explanation of the halo is that it is astrophysical in origin.

6. Comparison with Previous Results

The idea of a large-scale, yet non-isotropic component of Galactic γ-ray emission is not new. Strong *et al.* 1983 provides evidence for such a feature from the COS-B data after subtracting the estimated contribution from cosmic-ray/gas interactions. In Strong *et al.* 1983, it is noted that the effect is larger in the inner Galaxy, suggesting a Galactic, rather than local origin, with inverse Compton (IC) proposed as the emission mechanism. Strong 1984, however, investigates a possible local origin as well, citing the apparent north-south asymmetry of the emission as an indicator of a local source. Chen, Dwyer, and Kaaret 1996 also visit this problem by calculating the linear correlation of the γ-ray emission with the HI column density in eight large regions with $29.5° < |b| < 79.5°$ and noting that the y-intercept of the linear fits ("uncorrelated emission") shows some anisotropy in longitude. These authors also propose an IC origin, fitting

a model which includes the spatial distribution of 408 MHz emission, on the assumption that this traces the cosmic-ray electron distribution. Smialkowski, Wolfendale, and Zhang 1997 perform a similar analysis, and also show evidence for a high-latitude excess. Wright 1996 claims a weak anisotropy in the diffuse γ-ray background. Willis 1996 shows evidence for a γ-ray halo in EGRET data for $E > 100$ MeV by examining the the residual above the Maximum Likelihood model, consisting of known point source contributions, expected emission from cosmic-ray/matter interactions, a model for IC emission, and the isotropic γ-ray background. The residual, blurred by a Gaussian of width 5°, shows evidence for large-scale non-isotropic emission surrounding GC. Willis also constructs a "large-scale residual" by estimating the flux at every point on the sky from a fit only to data within 15° of that point, and then subtracting the predicted Galactic diffuse emission. Sreekumar *et al.* 1998 also note evidence for an extended excess about GC, following an analysis similar to that of Willis 1996.

If we compare our results with those of previous investigators, the case for an astrophysical origin of the halo is further strengthened. Previous authors (Strong *et al.* 1983; Strong 1984; Chen, Dwyer, and Kaaret 1996; Smialkowski, Wolfendale, and Zhang 1997; Willis 1996) have noted the following characteristics:

1. Anisotropic distribution of γ-ray flux above that implied by gas column densities.

2. A longitude distribution which appears to reach a maximum near the Galactic center.

3. A north-south asymmetry in the latitude distribution, with more flux appearing at positive latitudes.

These characteristics are also reflected in Figures 3, 4, and 5. That the different analyses of EGRET data give similar results is maybe not such a strong statement, as they all basically look

at residuals not correlated with gas, and would be subject to similar instrumental systematics. However, the similarity amongst EGRET results certainly argues that we are not seeing artifacts of any individual analysis. That COS-B sees the same basic characteristics (Strong *et al.* 1983) provides a more compelling argument for an astrophysical origin. Most notably, the orbit of COS-B was quite different than that of CGRO, being at $90°$ inclination (vs. $28.5°$), with a much larger perigee and eccentricity. If the halo and its characteristics were due to any sort of orbital or background systematics, it would seem a highly unlikely coincidence.

7. Discussion of potential astrophysical sources

If the halo is astrophysical, the next question is as to the source of the γ-rays. The possibilities are to some extent dependent on what we take as the "distance" to the halo, i.e., is it local or associated with the Galaxy on a large scale? The particular location and large-scale morphology certainly suggest the Galactic interpretation; a local feature with such characteristics would be highly coincidental. As suggested by Strong 1984, however, the latitude asymmetry may argue for a local origin. It is also possible that we are observing multiple phenomena along the same lines of sight. In the absence of arguments for a local origin (e.g., nearby molecular clouds with similar location and size), we shall focus our discussion on possible Galactic origins.

As discussed above, determination of the precise extent of the halo is hampered by the statistics and non-uniform exposure of the dataset, but if we take it as Galactic, then it clearly extends several kpc above and below the Galactic plane. Three obvious possibilities present themselves for an extended halo γ-ray source distribution:

1. Unresolved high latitude point sources

2. Inverse Compton emission

3. Gamma rays associated with particle dark matter (either baryonic or not)

This list is clearly not exhaustive, but represents possibilities which we have examined.

A halo population of sufficiently dim and numerous point sources might account for the observed γ-ray excess. The obvious candidates here would be Geminga-type pulsars, presumably ejected from the Galactic plane via asymmetric supernova explosions. Such scenarios have been discussed extensively in the context of γ-ray bursts. Starbursts at the Galactic center may have injected a large number of dimming pulsars into the Galactic halo (Hartmann 1995). One can argue in favor of such an explanation in terms of the characteristics of Geminga, e.g., nearly all of its luminosity is in the form of γ-rays. To constrain this scenario, one would need to generate an estimate for the total inegtrated (over 4π sr) flux from our halo, and assume 10^3-10^5 Geminga-like pulsars.

One might also postulate some other class of high latitude point sources which may generate the halo γ-ray emission. An intriguing possibility is that of primordial black holes (PBHs). As they evaporate, PBHs would produce γ-rays, leading to a diffuse γ-ray background Page and Hawking 1976. Clustering of PBHs around galaxies would lead to anisoptries in this background, most notably as observed from the Milky Way. Wright 1996 provides evidence for a weak anisotropy, and places limits on the PBH evaporation rate. Cline 1998 discusses this further, and notes that an extended halo population of PBHs could lead to a halo such as we observe, with a significant portion of the isotropic γ-ray background also due to PBH evaporation in the extended halo.

The possibility of high latitude inverse Compton (IC) emission has been discussed previously (see, e.g., Smialkowski, Wolfendale, and Zhang 1997, Chen, Dwyer, and Kaaret 1996, Strong 1984, Strong and Youssefi 1995, Willis 1996). The distribution of Galactic IC emission is not

well-understood, and it is unlikely that one can make a definitive statement as to whether or not IC is the emission mechanism without extensive modeling and further analysis. In a very recent paper, Moskalenko and Strong 1998 shows that IC in the framework of a hard electron spectrum is a viable candidate for explaining the general Galactic plane excess above 1 GeV. This paper additionally indicates that, at least for a longitudinally averaged profile, a model with a halo a few kpc in height reasonably accounts for the latitude profile up to high latitudes, from low to high energies (100 MeV - 1 GeV). The obvious next step (which we shall explore for a future paper) is to perform TIPSH analysis using a 2D version of this model (derived from a cosmic-ray propagation code) as the null hypothesis. Also, we note that IC profiles typically have a strong component in the Galactic plane (mostly in the GC region) in addition to high-latitude emission. If the standard model underestimates IC, then model fits would result in an *overestimate* of the contribution from cosmic-ray/matter interations. This may explain our results at lower energies, which show a systematically negative residual in the Galactic plane away from GC, but still strong evidence for large-scale high-latitude emission surrounding the GC region.

Some models of particle dark matter, both baryonic (De Paolis *et al.* 1995) and non-baryonic (Jungman, Kamionkowski, and Griest 1996), predict γ-ray emission as an annihilation or interaction product. Annihilations of pairs of weakly interacting massive particles (WIMPs) are expected to generate γ-rays (among other things) as final products (Jungman, Kamionkowski, and Griest 1996). The "smoking gun" in this case would be the detection of a high-energy line at the WIMP mass, due to the processes $\chi\chi \to \gamma\gamma$ and $\chi\chi \to Z\gamma$ (Ullio and Bergstrom 1998). We see no evidence for this below 10 GeV. A continuum spectrum is also expected as secondary products from the reaction $\chi\chi \to q\bar{q}$, however the signature of this continuum would be more difficult to detect.

The key question here is whether or not WIMP annihilation is at all a realistic candidate. The answer is a qualified "yes", with our result providing some constraints. If we assume a generic Galactic distribution of WIMPs which is smooth (no clumping, see e.g. Turner 1986 and Kamionkowski and Kinkhabwala 1997), we can arrive at a rough estimate of $\langle\sigma v\rangle$, the average of the product of the WIMP annihilation cross-section and relative velocities. For our result this turns out to be something like $O(10^{-25}) - O(10^{-24})$. If we ignore exotic phenomena, and assume for simplicity that the annihilation occurs only via the s-wave channel, the relic WIMP density is given by (Jungman, Kamionkowski, and Griest 1996)

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle\sigma_A v\rangle}, \qquad (5)$$

where the Hubble constant is given as $100h$ km s^{-1} Mpc^{-1} and σ_A is the total WIMP annihilation cross-section. For the "standard" cosmological model with $\Omega = 1, h \simeq 1$, the annihilation cross-section above is far too large for WIMPs to account for an interesting quantity of dark matter (see also Cline 1998). One way out of this is to have clumpy dark matter, as discussed in Wasserman 1996, Gurevich and Zybin 1997, and in more recently in detail for large classes of supersymmetric (SUSY) WIMP models in Bergström, Edsjö, and Ullio 1998 and Bergström *et al.* 1998. The reason for this is that the γ-ray intensity goes as the *square* of the WIMP density, and so modest local density enhancements can lead to large increases in γ-ray emissivity. In particular, Bergström *et al.* 1998 notes that it is the combination of the γ-ray and cosmic-ray antiproton intensities which place the best constraints on SUSY and clumping parameters. Another way to make WIMPs more viable is to modify the cosmological model. In fact, recent results from high-redshift supernova surveys (Filippenko and Riess 1998) indicate $h \simeq 0.65$ and $\Omega_{matter} \simeq 0.3$, which brings the implied annihilation cross-section at least closer to what we

calculate. In fact, Gondolo 1998 has shown that one can explain the observed halo quite nicely following a similar approach. So this remains an open question.

Finally, we come to the baryonic dark matter hypothesis. A number of authors have proposed that Galactic dark matter may be in the form of cold, dark molecular clouds (see e.g. Pfenniger, Combes, and Martinet 1994, Gerhard and Silk 1996). Walker and Wardle 1998 have postulated that extreme scattering events in the radio may be attributed to photo-ionized electrons in such clounds as they pass through the line of sight. Walker 1998 notes that collisions amongst such clouds naturally leads to a cored halo distribution, and may form the physical basis for the Tully-Fisher relation. De Paolis *et al* 1995 also suggest that a significant portion of dark matter may come in the form of clusters of MACHOs and/or cold H_2 molecular clouds. If in the form of cold H_2 clouds, then we expect some γ-ray emission resulting from cosmic ray protons and the reactions $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$. De Paolis *et al* make an estimate of the distribution of high latitude cosmic ray protons, and predict the γ-ray flux above 1 GeV at the Galactic poles to be $\Phi_\gamma(90°) \simeq \epsilon 1.7 \times 10^{-6}$ cm^{-2} s^{-1} sr^{-1}, where ϵ is some efficiency factor included to account for uncertainties in the CR proton distribution.

Though exposure artifacts at the poles prevent us from making a direct comparison, this estimate is clearly in the neighborhood of what we have observed. One question which arises in this scenario is whether or not one expects to see many γ-rays: if the CR protons have largely outward momenta, so too will the γ-rays, resulting in a small ϵ. In order to get the γ-ray flux we observe, some sort of trapping of CR protons in the Galactic halo must occur. Simpson 1998 has recently reported that, based on measurements of isotopic abundances in cosmic-rays (e.g., $^{26}Al/^{27}Al$), that cosmic-ray lifetimes are perhaps a factor of four larger than previously thought, and that the cosmic-rays are traversing

an average ISM density smaller than that observed for the Galaxy. Strong and Moskalenko 1998 also report, based on $^{10}Be/^9Be$ measurements and comparison with cosmic-ray propagation models, that the height of the halo propagation regions is > 4 kpc. One interpretation of this is that cosmic-rays are trapped in the low-density halo, making the De Paolis *et al.* 1995 scenario somewhat more appealing. There are clearly large uncertainties associated with this hypothesis, but it seems an intriguing avenue for further study.

8. Future Directions

The establishment of the existence and (to some extent) the spatial distribution of the halo indicates several lines of future research. Clearly one step to be taken in the near future is to do the TIPSH analysis on data taken over smaller energy bins, to try and establish (at least qualitatively) the energy dependence of the halo morphology. We also note that the Galactic diffuse model used here is only one choice amongst many. Future analyses will use different and more sophisticated hypotheses, as well as include the effects of point sources in the null hypothesis. Another direction is in the application on parametric analyses to the same data to fill in that information which is difficult to obtain non-parametrically. This includes quantitative estimates of fluxes and errors, as well as parameterizations of the halo morphology as dictated by various physical models. Hypotheses as to the origin of the halo can potentially be rejected on the basis of spatial/spectral behavior. Also, if the halo truly is Galactic, estimates of the extragalactic γ-ray background may be impacted. Galactic halo models which give rise to γ-ray emission not only include a bulge-like component as we've seen here, but generally larger scale emission as well. While such emission may not be precisely isotropic, it is typically dim (compared to the bulge component) and spatially more slowly varying; as such it may be statisti-

cally indistinguishable from isotropic emission in the EGRET data. In our very simple parametric fit above, the estimate of the isotropic emission changed by $\sim 25\%$ depending on whether or not a halo component was included, so this possibility is in no way negligible.

We saw above that the key limitation to understanding (at least non-parametrically) the spatial distribution of the halo is the highly non-uniform exposure of EGRET observations. It is unlikely this will improve much, given that EGRET is basically out of spark chamber gas. In principle we could include more observations from later CGRO cycles, but these contain rather little additional information, and generally don't serve to even out the exposure. The upcoming GLAST mission may provide better data for these types of studies. GLAST will be more sensitive over a larger energy band, and further, if operated in a scanning (as opposed to pointed) mode, will yield an all-sky exposure considerably more uniform than EGRET's, thus removing a key systematic. Detailed understanding of what GLAST may be able to do in this context remains the subject of future studies.

9. Conclusions

We have presented strong statistical evidence for a large scale anisotropic excess in high energy γ-rays. Examination of our maps indicates that this excess may originate in the Galactic halo, though our results in no way rule out a local origin. The spectrum appears to be broadband; detailed investigation of the spectral properties will be the subject of future work. The origin of the halo is unclear. Emission from inverse Compton in a large halo Moskalenko and Strong 1998 appears to be a good candidate but it remains to be seen whether it can account for the entire observations in detail. A definitive answer on this topic will perhaps require a "smoking gun" in this or another energy band, or may have to wait for the GLAST mission. Further, as noted by previous authors (Smialkowski, Wolfendale,

and Zhang 1997; Chen, Dwyer, and Kaaret 1996; Strong *et al.* 1983), the existence of such an extended excess may impact estimates of the extragalactic γ-ray background.

10. Reproducible Research, Color Figures

Data and software to reproduce the results of this paper can be found at `http://tigre.ucr.edu/halo/repro.html`.

Color versions (in JPEG format) of the figures are available at `http://tigre.ucr.edu/halo/paper.html`.

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Fig. 1.— Two-dimensional Haar wavelets, encoding image variations in the a) horizontal, b) vertical, and c) diagonal directions.

Fig. 2.— Galactic diffuse model used in the null hypothesis (isotropic component is not included), truncated at the same flux as Figure 3. Contour values are flux in units of ph cm^{-2} s^{-1} sr^{-1}.

Fig. 3.— Contours are in units of 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) Positive TIPSH residual for $E > 1$ GeV, unscaled Galactic diffuse model. Fluxes have been truncated at 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. b) Negative TIPSH residual as for (a). Flux truncated at -2×10^{-6} ph cm^{-2} s^{-1} sr^{-1}.

Fig. 4.— Contours are in units of 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) Positive TIPSH residual for $E > 1$ GeV, Galactic diffuse model scaled by 1.4. Fluxes have been truncated at 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. b) Negative TIPSH residual as for (a). Flux truncated at -2×10^{-6} ph cm^{-2} s^{-1} sr^{-1}.

Fig. 5.— Contours are in units of 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) Positive TIPSH residual for $E > 1$ GeV, Galactic diffuse model scaled by 1.2. Fluxes have been truncated at 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. b) Negative TIPSH residual as for (a). Flux truncated at -2×10^{-6} ph cm^{-2} s^{-1} sr^{-1}.

Fig. 6.— Contours evenly spaced between 0 and 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) Model of inverse Compton emission above 1 GeV. b) TIPSH recovered flux distribution for simulated data including (a).

Fig. 7.— EGRET exposure for CGRO Phases 1-4.

Fig. 8.— Truncated denoised residual with Phase 1-4 exposure overplotted as dotted contours.

Fig. 9.— TIPSH residual for simulated data based on the predicted diffuse emission. Units are counts.

Fig. 10.— Fractional deviation in TIPSH estimated flux for simulated data consisting of an isotropic excess at the level of the measured isotropic background. The exposure factor is overplotted as contours.

Fig. 11.— Contours are in units of 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) 40% scaled standard Galactic diffuse model. TIPSH residual for simulated data based on the predicted emission with an excess of 40% Galactic diffuse, using the standard prediction as the null hypothesis.

Fig. 12.— Ratio of the inverse Compton model in Figure 6a to the recovered flux distribution in Figure 6b.

Fig. 13.— Contours are in units of 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) Positive TIPSH residual for $100 < E < 300$ MeV, unscaled Galactic diffuse model. Fluxes have been truncated at 2×10^{-5} ph cm^{-2} s^{-1} sr^{-1}. b) Negative TIPSH residual as for (a). Flux truncated at -10^{-5} ph cm^{-2} s^{-1} sr^{-1}.

Fig. 14.— Contours are in units of 10^{-5} ph cm^{-2} s^{-1} sr^{-1}. a) Positive TIPSH residual for $300 < E < 1000$ MeV, unscaled Galactic diffuse model. Fluxes have been truncated at 1.5×10^{-5} ph cm^{-2} s^{-1} sr^{-1}. b) Negative TIPSH residual as for (a). Flux truncated at -5×10^{-6} ph cm^{-2} s^{-1} sr^{-1}.

Fig. 15.— The dark curves bound regions where Earth albedo contamination is expected to be greatest. Note no particular excess in these regions, nor correlation with the spatial distribution of the halo.

Wavelet scale	No. wavelets det. (data)			No. wavelets det. (null)		
(pixels)	Hor	Vert	Diag	Hor	Vert	Diag
2	336	325	190	0	0	0
4	846	965	537	0	0	0
8	2307	2831	1783	0	0	0
16	7864	8387	5767	0	0	0
32	25166	26948	20552	0	0	0
64	1.0×10^5	1.1×10^5	78538	8	0	0
128	3.3×10^5	3.9×10^5	3.1×10^5	1	0	0
256	7.8×10^5	9.2×10^5	7.4×10^5	0	0	0
512	7.9×10^5	8.0×10^5	6.1×10^5	0	0	0

Table 1: Number of wavelets detected (i.e., those that passed threshhold) for actual data (in the case given in Figure 5) and for simulated data generated by the null hypothesis, as a function of the wavelet direction (horizontal, vertical, or diagonal). The level-wise false detection rate (FDR) was set at 10^{-4}. Note that the number of detections for the data is much higher than that for the null, which is much more in line with what we expect for the chosen FDR. The detection rates above are averaged over the image shifts. This adds a slight subtlety, since the tests at different shifts are *not* independent, so a wavelet that is detected in one shift may very well also be detected in nearby shifts.

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