Charles D. Dermer

High-Energy Cosmology
γ rays and neutrinos from beyond the galaxy

Received: date / Accepted: date

Abstract Our knowledge of the high-energy universe is undergoing a period of rapid change as new astronomical detectors of high-energy radiation start to operate at their design sensitivities. Now is a boomtime for high-energy astrophysics, with new discoveries from Swift and HESS, results from MAGIC and VERITAS starting to be reported, the upcoming launches of the γ-ray space telescopes GLAST and AGILE, and anticipated data releases from IceCube and Auger.

A formalism for calculating statistical properties of cosmological γ-ray sources is presented. Application is made to model calculations of the statistical distributions of γ-ray and neutrino emission from (i) beamed sources, specifically, long-duration GRBs, blazars, and extragalactic microquasars, and (ii) unbeamed sources, including normal galaxies, starburst galaxies and clusters. Expressions for the integrated intensities of faint beamed and unbeamed high-energy radiation sources are also derived. A toy model for the background intensity of radiation from dark-matter annihilation taking place in the early universe is constructed. Estimates for the γ-ray fluxes of local group galaxies, starburst, and infrared luminous galaxies are briefly reviewed.

Keywords Gamma-ray bursts · Clusters of Galaxies · Starburst Galaxies · Blazars · Microquasars

PACS 95.85.Ry · 98.70.Rz · 95.85.Pw · 98.80.-k

1 Introduction

The next decade is likely to be remembered as the pioneering epoch when the first high-energy (PeV – EeV) ν sources were detected with IceCube [1] and its km-scale Northern hemisphere counterpart, and when the problem of cosmic-ray origin was finally solved through identification of the sources of cosmic rays at all energies, from GeV – TeV nucleonic cosmic rays accelerated by supernova remnant shocks of various types, to extragalactic super-GZK γ-ray and ν sources.

The cosmology of γ-ray sources in the ≈ 10 MeV – 10 GeV range is treated here. The lower bound of this energy range ensures that the γ rays originate from non-thermal processes, and the upper bound is defined by the energies of photons that originate from sources at redshifts z ≫ 1 without significant γγ → e+e− attenuation in reactions with photons of the extragalactic background light (EBL). The formalism also applies to other nonthermal radiations, to ultra-relativistic particles, including PeV – EeV ν and ultra-high energy neutrinos, and to multi-GeV – EeV photons by taking into account attenuation and reprocessing of the γ-rays on the EBL.

The problems treated here are the

1. Event rate of bursting sources;
2. Size distribution of bursting sources; and
3. Apparently diffuse intensity from unresolved sources.

I outline applications of these results to beamed sources, including GRBs, blazars and extragalactic microquasars, and unbeamed sources, including star-forming galaxies and merging clusters of galaxies.

This paper, prepared for the conference proceedings of the Multi-Messenger Approach to High Energy Gamma-Ray Sources, held 4 – 7 July 2006 in Barcelona, Spain, addresses in a more formal manner the points I was to cover, including blazars which I could not neglect (see Ref. 2 for a review of blazar emissions). The formalism applies to analysis of γ-ray and ν data from GLAST, IceCube, and other high-energy astroparticle observatories.
2 Event Rate of Bursting Sources

The Robertson-Walker metric for a homogeneous, isotropic universe can be written as
\[
\frac{ds^2}{c^2dt^2} = R^2(t)\left( \frac{dr^2}{1-\frac{r^2}{R^2}} + r^2d\Omega^2 \right),
\]
where \( r \) is a comoving coordinate and \( R(t) \) is the expansion scale factor. The most convenient choice is to have \( r \) take the value of physical distance at the present epoch so that \( R(t) = R = 1 \), and denote \( R_* = R(t_*) \) at emission time \( t_* \leq t \) (stars denote the emission epoch). Material structures reside for the most part on constant values of the comoving coordinates, whereas light and ultra-relativistic particles cannot be confined to such coordinates. From the definition of redshift \( z = (\lambda - \lambda_\gamma)/\lambda_\gamma \), we have \( 1 + z = \omega/\epsilon = \Delta t/\Delta t_* = R/R_* \), where \( \epsilon \) refers to the energy of the photon or ultrarelativistic particle. The curvature of space is determined by the curvature constant \( k \), with \( k = 0 \) for flat space.

The proper volume element of a slice of the universe at time \( t_* \) is, from eq. (1) for a flat universe,
\[
dV_* = R_*^3r_*^2dr = dr_*^2d\Omega_* = cdt_*dA_*.
\]
Comparing with the definition of \( d\Omega = (Rr)^2d\Omega \) and noting that \( d\Omega_* = d\Omega \) in the absence of cosmic shear, we have
\[
\frac{dA_*}{dA} = \frac{1}{(1+z)^2}.
\]

The directional event rate, or event rate per sr, is
\[
\frac{d\dot{N}}{d\Omega} = \frac{1}{4\pi} \int dV_* \dot{n}_*(z) \left| \frac{dt_*}{dt} \right| = c \int_0^\infty dz \frac{dt_*}{dz} (R_*r)^2\dot{n}_*(z),
\]
where the burst emissivity \( \dot{n}_*(z) \) gives the rate density of events at redshift \( z \). An expression for \( (R_*r)^2 \) can be derived by recalling the relationship between energy flux \( \Phi_E \) and luminosity distance \( d_L \), namely
\[
\frac{d\dot{E}}{dAt} = \Phi_E = \frac{L_*}{4\pi d_L^2} = \frac{d\dot{E}_*}{4\pi d_*^2 \dot{t}_s} = \frac{(1+z)^2}{4\pi d_L^2} \Phi_E dA,
\]
so that with eq. (3),
\[
(R_*r)^2 = \frac{d_*^2(z)}{(1+z)^2}.
\]

For a flat \( \Lambda \)CDM universe,
\[
\frac{dz}{dt_*} = H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda},
\]
where \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27 \) and \( \Omega_\Lambda = 0.73 \) are the ratios of the energy densities of total mass, including both normal matter and dark matter, and dark energy, respectively, compared to the critical density for the flat \( \Lambda \)CDM cosmology of our universe.

The proper volume element of a slice of the universe at time \( t_* \) is, from eq. (1) for a flat universe,
\[
dV_* = R_*^3r_*^2dr = dr_*^2d\Omega_* = cdt_*dA_*.
\]
Comparing with the definition of \( d\Omega = (Rr)^2d\Omega \) and noting that \( d\Omega_* = d\Omega \) in the absence of cosmic shear, we have
\[
\frac{dA_*}{dA} = \frac{1}{(1+z)^2}.
\]

The directional event rate, eq. (4), becomes
\[
\frac{d\dot{N}}{d\Omega} = c \int_0^\infty dz \frac{dt_*}{dz} (R_*r)^2\dot{n}_*(z),
\]
where the burst emissivity \( \dot{n}_*(z) \) gives the rate density of events at redshift \( z \). An expression for \( (R_*r)^2 \) can be derived by recalling the relationship between energy flux \( \Phi_E \) and luminosity distance \( d_L \), namely
\[
\frac{d\dot{E}}{dAt} = \Phi_E = \frac{L_*}{4\pi d_L^2} = \frac{d\dot{E}_*}{4\pi d_*^2 \dot{t}_s} = \frac{(1+z)^2}{4\pi d_L^2} \Phi_E dA,
\]
so that with eq. (3),
\[
(R_*r)^2 = \frac{d_*^2(z)}{(1+z)^2}.
\]

For a flat \( \Lambda \)CDM universe,
\[
\frac{dz}{dt_*} = H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda},
\]
where \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27 \) and \( \Omega_\Lambda = 0.73 \) are the ratios of the energy densities of total mass, including both normal matter and dark matter, and dark energy, respectively, compared to the critical density for the flat \( \Lambda \)CDM cosmology of our universe.

![Fig. 1](https://example.com/fig1.png)

Different structure formation histories (SFHs) considered in this paper. As labeled, CCSFH: constant comoving SFH; LSFR: lower star formation rate; USFR: upper SFR; SFH HB: SFH history from Ref. [2]; SFH IR: SFH of IR luminous galaxies [11]; GRB SFHs: range of SFHs of GRBs used to fit Swift and pre-Swift GRB distributions [3]; SFH BL: SFH of BL Lac objects [5]. These rates are poorly known at \( z \gg 1 \).

The directional event rate, eq. (4), becomes
\[
\frac{d\dot{N}}{d\Omega} = c \int_0^\infty dz \frac{dt_*}{dz} (R_*r)^2\dot{n}_*(z),
\]
where the burst emissivity \( \dot{n}_*(z) \) gives the rate density of events at redshift \( z \). An expression for \( (R_*r)^2 \) can be derived by recalling the relationship between energy flux \( \Phi_E \) and luminosity distance \( d_L \), namely
\[
\frac{d\dot{E}}{dAt} = \Phi_E = \frac{L_*}{4\pi d_L^2} = \frac{d\dot{E}_*}{4\pi d_*^2 \dot{t}_s} = \frac{(1+z)^2}{4\pi d_L^2} \Phi_E dA,
\]
so that with eq. (3),
\[
(R_*r)^2 = \frac{d_*^2(z)}{(1+z)^2}.
\]

For a flat \( \Lambda \)CDM universe,
\[
\frac{dz}{dt_*} = H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda},
\]
where \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27 \) and \( \Omega_\Lambda = 0.73 \) are the ratios of the energy densities of total mass, including both normal matter and dark matter, and dark energy, respectively, compared to the critical density for the flat \( \Lambda \)CDM cosmology of our universe.
3 Size Distribution

After substituting eq. (9) into eq. (8) and placing limits on the integrals in accordance with detector specifications, model distributions of source properties can be derived, in particular, the size distribution.

3.1 Beamed Sources

A distinction between two types of models for relativistically beamed sources needs to be made. A blast-wave model is usually considered for GRB sources. Here the half-angular extent of a spherical blast-wave jet is assumed to be much greater than the Doppler beaming angle \( \theta_\text{D} \sim 1/\Gamma \), so that \( \theta_j \gg \theta_\text{D} \), where \( \Gamma \) is the bulk Lorentz factor of the outflow. In this case, the observer is limited to detection of a GRB if the direction from the source to the observer intercepts the solid angle of the blast wave. By contrast, in a blob model, as is usually considered in blazar studies, \( \theta_j \ll \theta_\text{D} \), and the beaming properties of the jet are determined primarily by the Doppler factor

\[
\delta_\text{D} = \left[ \Gamma(1 - \beta \mu) \right]^{-1},
\]

where \( \beta \Gamma = \sqrt{\Gamma^2 - 1} \), and \( \arccos \mu \) is the observer’s angle measured with respect to the jet axis. Interpreting emissions within a blast-wave and blob framework provide the simplest models that can be used to systematically analyze the statistics of GRBs, blazars, radio galaxies, and microquasars within the context of a physical (rather than a phenomenological) model.

Gamma Ray Bursts If a GRB releases an amount of \( \gamma \)-ray energy \( \mathcal{E}_{\gamma} \) that is deposited in a waveband to which a GRB detector is sensitive, then an event is recorded when the source flux

\[
\frac{\mathcal{E}_{\gamma}}{4\pi d_L^2(z)(1 - \mu_j)} \Delta \ell \lambda_\text{b} \gtrsim f_\epsilon,
\]

where \( f_\epsilon \) is the \( \nu F_\nu \) threshold sensitivity of the GRB detector. The emission into a jet with opening half-angle \( \theta_j \) has the effect, for constant \( \mathcal{E}_{\gamma} \), to enhance the received flux by a factor \( (1 - \mu_j)^{-1} \), though the chance of the jet being in the line of sight to the observer (compared to an isotropically emitting source) is reduced by the factor \( 1 - \mu_j \). The term \( \lambda_\text{b} \) is a bolometric correction factor made in lieu of a full spectral treatment.

The GRB size distribution for the blast-wave geometry is given by

\[
dN_{\text{GRB}}(> f_\epsilon) = 2c\hat{\mu}_{\text{GRB}} \int_0^\infty dz \left| \frac{dt_\epsilon}{dz} \right| \frac{d\mathcal{E}_\gamma(z) \Sigma_{\text{GRB}}(z)}{(1 + z)^2} \times \int_{\max(0, \hat{\mu}_j)}^{1} d\mu_j \, g(\mu_j) \left(1 - \mu_j\right),
\]

where \( g(\mu_j) \) is the normalized distribution function of GRB jet opening angles, and

\[
\hat{\mu}_j = 1 - \frac{\mathcal{E}_{\gamma}}{4\pi d_L^2(z) \Delta \ell \lambda_\text{b} f_\epsilon},
\]

Le and Dermer (2006) have used this approach to analyze the redshift and opening-angle (\( \theta_j \)) distributions of GRB detectors, including missions before Swift compared with distributions measured with Swift. They find that the comoving rate densities of GRBs must undergo positive evolution to at least \( z \gtrsim 5 - 7 \) to account for the difference in distributions of pre-Swift and Swift-detected GRBs with redshift information. By contrast, the star-formation history of the universe as inferred from blue and UV luminosity density, peaks at \( z \approx 2 - 3 \) and seems to decline at larger redshift [7]. Le and Dermer (2006) find this SFH to be incompatible with the statistics of GRBs with measured redshifts. Thus the SFH of GRBs is apparently very different than the integrated high-mass star formation history of the universe.

This approach can be suitably adapted to the short, hard class of GRBs to infer the rate density of this class of GRBs. A large data set, accumulated after a long Swift lifetime, can in principle distinguish between models involving compact-object coalescence and accretion-induced collapse of neutron stars.

Blazars A considerable simplification to the emission properties of blazars results by approximating the \( \nu F_\nu \) fluxes detected from a distant source by the expression

\[
f_\epsilon^{\text{proc}} = \frac{\ell'_\epsilon \delta^3 \Sigma_{\nu}^{\alpha\nu}}{d_L^2(z)} \geq f_\epsilon
\]

[8,5], where \( \ell'_\epsilon \) is the comoving directional power and \( f_\epsilon \) represents the characteristic flare size, in this case, in units of energy flux. The beaming factor indices for individual radiating blobs are

\[
q = \left\{ \begin{array}{ll}
(p + 5)/2, & \text{synchrotron/SSC} \\
p + 3 & \text{EC}
\end{array} \right.
\]

The synchrotron/SSC factor applies to blazars where the \( \gamma \)-rays are from the synchrotron self-Compton processes, specifically X-ray–selected blazars and TeV blazars. The external Compton (EC) beaming factor applies to blazars where the \( \gamma \)-rays are ambient photons, external to the jet, that intercept the jet and Compton-scattered by the jet electrons. Examples of ambient radiation fields are the accretion disk photons, and accretion-disk photons that are scattered by surrounding dust and gas.

From eqs. (8) and (9), the blazar flare size distribution is given by the expression

\[
dN_{\text{bl}}(> f_\epsilon) = 2c\hat{\mu}_{\text{bl}} \int_0^\infty dz \left| \frac{dt_\epsilon}{dz} \right| \frac{d\mathcal{E}_\gamma(z) \Sigma_{\text{bl}}(z)}{(1 + z)^2} \times
\]

\[
\int_{\max(0, \hat{\mu}_j)}^1 d\mu_j \, N(\Gamma; z) \int_{\max(0, \hat{\mu}_j)}^1 d\ell'_\epsilon \, N(\ell'_\epsilon; z) \left[1 - \max(-1, \hat{\mu}_j)\right].
\]
where
\[ \dot{\mu} = \frac{1}{\beta} \left[ 1 - \frac{\ell'_c \epsilon \dot{\epsilon}}{d_f} \right]^{1/\eta}. \] (17)

Specification of the \( z \)-evolution of the normalized distribution functions \( N(\Gamma'; z) \) and \( N(\ell'_c; z) \) due to number evolution or luminosity evolution, respectively, connects this formulation back to the cosmology of physical processes and the growth of structure taking place in the early universe.

Refs. [5] uses this approach to analyze the redshift and size distribution of EGRET \( \gamma \)-ray blazars (see also [9]), divided into flat spectrum radio quasars (FSRQs) and BL Lac objects (BLs). Evolutionary behaviors are found that characterize the measured redshift and size distributions of FSRQs and BLs. The behavior of the BLs is in accord with the conjecture that BLs are late stages of the formation and evolutionary history of FSRQs, and before that, IR luminous galaxies [10][11]. See Ref. [5] for predictions of the number of blazars that GLAST will detect.

**Microquasars** \( \gamma \)-ray emission from microquasars could be visible from nearby galaxies if the bulk Lorentz factors in microquasar jets were large enough that the received flux from a microquasar in another galaxy was brighter than threshold. The size distribution of microquasar flares can be written by taking the limit \( z \ll 1 \) of the blazar expression, eq. (16), to give
\[ \frac{dN_{\mu q}}{d\Omega} (> f_c) = \frac{2c^3 \dot{\mu}_{\mu q}}{H_0^2} \int_0^\infty dz \left[ 1 - \max(-1, \dot{\mu}) \right] N(\Gamma'; z), \] (18)
which assumes an averaging over the small scale mass distributions of nearby galaxies. The integration in \( \ell'_c \) is removed in this expression, compared with eq. (16), by assuming an Eddington limitation on the accretion flow. Approximating the emission spectrum by a single power law with \( \nu F_\nu \) index \( \alpha \), in the comoving energy range \( \epsilon'_0 < \epsilon' < \epsilon'_1 \), the directional luminosity is therefore limited by
\[ \ell'_c \lesssim \frac{2 \times 10^{38} mc}{4\pi \lambda_0} \text{ ergs s}^{-1} \text{ sr}^{-1}, \] (19)
noting that the emission is beamed into \( \approx \Gamma^{-2} \) of the full sky, and that the radiated power is boosted by \( \Gamma^2 \) due to bulk motion of the plasma. Here \( m_c \) is the Chandrasekhar mass (in units of 1.4 \( M_\odot \)) of the compact object in the microquasar.

### 3.2 Unbeamed Sources

For \( \gamma \)-ray emission from unbeamed sources, like the Milky Way galaxy, normal galaxies, and all but the most dusty and heavily extinguished starburst and infrared luminous galaxies (whose ambient radiation would attenuate the \( \gamma \) rays), we can count the number of source detections above a threshold flux \( f_e \), following eq. (16), to give:
\[ \frac{dN_i}{d\Omega} (> f_e) = cn_i \int_0^\infty dz \left| \frac{d\ell}{dz} \right| \frac{d_{\ell}^2(z) L_i(z)}{(1+z)}. \] (20)
The luminosity function of the unbeamed source population is denoted by \( N(L_\ast; z) \), where \( L_\ast = \int_0^\infty d\epsilon_i L(\epsilon_i) \) is the total luminosity of the source. Writing the spectral luminosity \( L_\ast(\epsilon_i) = L_\ast(\epsilon_e^{-1+\alpha}) \) gives the threshold condition
\[ \frac{L_\ast(\epsilon_e)}{4\pi d^2_L} \geq f_e \] (21)
for detection of these sources. For a power-law spectrum with low- and high-energy cutoffs, this expression can be used to impose the lower limit \( L_{\ast\min} \) in eq. (21), which also assumes an average over large volumes. For normal galaxies, volumes of radii of several Mpc may be large enough for this averaging. For clusters of galaxies, an averaging size scale of many tens of Mpc is needed, as calculations at scales less than \( z \sim 0.02 \) are subject to strong fluctuations due to the low density of clusters of galaxies in this volume.

### 4 Intensity of Unresolved Sources

The differential spectral flux
\[ d\phi(\epsilon) = \frac{dN}{dAdde} = \frac{\dot{\epsilon}_s(\epsilon_s; z) d\epsilon_s dt_s dV_\ast}{dAdde}. \] (22)
Using the relations \( dV_\ast = d\epsilon dA_\ast = cdt_s dA/(1+z)^2 \) from eq. (3), \( \epsilon_s = \epsilon(1+z) \equiv \epsilon_z \), and \( dt = dt_s(1+z) \), we have
\[ \phi(\epsilon) = \frac{c \int_0^\infty d\epsilon_z}{d\ell_s} \frac{\dot{\epsilon}_s(\epsilon_s; z)}{(1+z)^2}. \] (23)
Because the “\( \nu F_\nu \)” intensity \( \epsilon I_\ell = mc^2 \epsilon^2 \phi(\epsilon)/4\pi \),
\[ \epsilon I_\ell = \frac{c}{4\pi} \int_0^\infty d\epsilon \left| \frac{d\ell}{dz} \right| \frac{m_c c^2 \dot{\epsilon}_s^2(\epsilon_s; z)}{1+z}. \] (24)

**GRBs** The diffuse intensity of GRBs is, from eq. (24) and assuming a two-sided GRB jet source,
\[ \epsilon I^{\text{GRB}}(\ell_c) = \frac{m_c c^2 \dot{\epsilon}_s^2 n_{\text{GRB}}}{4\pi} \int_0^\infty d\epsilon \left| \frac{d\ell}{dz} \right| \frac{\Sigma_{\text{GRB}}(z)}{1+z} \times \int_0^{\min(1,\dot{\mu})} d\mu_j g(\mu_j) (1-\mu_j) \epsilon_j^2 N(\epsilon_s; \mu_j). \] (25)
For a flat \( \nu F_\nu \) spectrum that covers the waveband of the GRB detector, \( m_c c^2 \epsilon_s^2 N(\epsilon_s; \mu_j) = \mathcal{E}_\gamma/|\lambda_0(1-\mu_j)| \), and \( \dot{\mu}_j \) is given by eq. (14).
Using the parameters derived from analyses of statistical distributions of GRB data [6], one can then calculate the integrated \( \gamma \)-ray background from GRBs which, as we shall see, is a negligible fraction of the diffuse isotropic \( \gamma \)-ray background. Suitable scalings are adopted in model calculations of \( \nu \) emissions from GRBs to calculate the diffuse \( \sim 100 \text{ TeV} - \text{EeV} \) \( \nu \) intensity from GRBs [12].

**Blazars** The total intensity from two-sided blazar jet sources, which will include emission from aligned and misaligned blazars and radio galaxies, is given in the blob framework by

\[
\epsilon I_{\nu}^{\text{bl}} = \frac{c}{2\pi} \int_0^\infty dz \frac{|d\epsilon_*|}{dz} \frac{1}{1+z} \times \int d\Omega' c_2 q_d(\epsilon_*, \Omega'; z),
\]

where \( q_d(\epsilon_*, \Omega'; z) \) is the directional spectral flux of a blazar jet, given in the blob framework by

\[
\epsilon^2 q_d(\epsilon_*, \Omega'; z) = \ell'_e(\epsilon) n_d(\epsilon) \delta^3_D \epsilon^2_\nu.
\]

[5] Here \( n_d(\epsilon) \) is the comoving density of blazar sources. The intensity of unresolved blazars and radio galaxies is then

\[
\epsilon I_{\nu}^{\text{bl}}(< f_e) = \frac{c^2}{\beta_\mu G} \int_0^\infty dz \frac{n_d(\epsilon)}{(1+z)^{1-\alpha_\nu}} \int_1^\infty d\Gamma N(\Gamma; z) \times \int d\ell' N(\ell'_e; z) \left\{ [1-\beta \min(1, \mu)]^{-1-q} - (1+\beta)^{-q} \right\},
\]

with \( \mu \) given by eq. [17].

**Microquasars** The intensity from microquasars is given essentially by eq. [20], though with a very different local rate density \( n_{\text{mq}} \), SFH \( \Sigma_{\text{mq}} \), and distribution in \( \Gamma \) and \( \ell'_e \).

**Unbeamed Sources** If \( N(\Gamma_i; z) \) is the redshift-dependent luminosity function of unbeamed \( \gamma \)-ray sources, such as normal galaxies and starburst and IR luminous galaxies, then the diffuse intensity from these sources over cosmic time is

\[
\epsilon I_{\nu}^{\text{iso}}(< f_e) = \frac{c}{4\pi} \int dz \frac{m_\epsilon c^2 \epsilon^2 n_{\text{iso}}(\epsilon_*, z)}{1+z} \times \int_0^{L_{\text{min}}^*(z)} dL_* N(L_*; z),
\]

where now \( L_{\text{min}}^*(z) \) again depends on detector characteristics according to the prescription of eq. [21].

It is interesting to note that the factor \( |d\epsilon_*|/dz \) associated with the passage of time in an expanding universe saves us from Olbers’ paradox. In this formulation, the logarithmically divergent integrated intensity emitted by radiant sources distributed uniformly throughout the universe is blocked by the redshifting of radiation and the finite age of the universe.

**GZK Neutrino Intensity** The intensity of \( \nu \) formed as photopion secondaries in the interaction of UHECRs with the EBL is given, starting with eq. [24], in the form

\[
\epsilon I_{\nu}^{\text{GZK}} = m_\epsilon c^2 \int_0^\infty dz \frac{d\epsilon_*}{dz} \frac{n_G Z K(\epsilon_*, \Omega; z)}{(1+z)^2}.
\]

The production spectrum of secondary \( \nu \) is given by

\[
\frac{\dot{n}_{G Z K}(\epsilon_*, \Omega; z)}{c} = \sum_j \int d\Omega \int_0^\infty d\epsilon_* n_{ph}^*(\epsilon_*, \Omega; z) \frac{d\sigma_j(\epsilon)}{d\epsilon}.
\]

The sum is over various channels leading to production of neutrinos, and \( n_{ph}^*(\epsilon_*, \Omega; z) \) and \( n_{ph}^*(\gamma_*, \Omega'_p; z) \) are the evolving EBL and UHECR proton spectra, respectively (generalization to ions is straightforward). Ref. [13] uses this formalism to calculate the GZK \( \nu \) intensity under the assumption that the sources of UHECRs are GRBs.

The GZK \( \gamma \)-ray intensity can be calculated according to this formalism by convolving the redshift-dependent differential intensity with a source function that represents the emergent \( \gamma \)-ray spectrum after reprocessing on the background radiation field. This will produce a complete model of UHECRs, which consists of a fit to the UHECR spectrum, a prediction for the GZK \( \nu \) flux, and the predicted diffuse \( \gamma \)-ray spectrum—which must be less than the diffuse EBL at \( \gamma \)-ray energies [14].

**Dark Matter Annihilation** Astrophysical searches for signatures of dark matter annihilation target regions of enhanced (dark) matter density, such as cuspy cores of quasi-spherical galaxies, for example, dwarf ellipticals. Because of its proximity, even the center of the Milky Way is considered to be a hopeful site of dark matter annihilation, in spite of perturbing warps and bars in its normal matter distribution. One region where unavoidably high densities of dark matter had to persist was in the early universe.

Up to now, we have considered classes of sources whose density scales as a redshift-dependent structure formation rate \( \Sigma_i(z) \) for sources of type \( i \). To first approximation, source density is proportional to the total normal matter content, so that the factor \( (1+z)^3 \) is removed and the SFH is described in terms of the comoving rate density. Dark matter annihilation scales as the square of the density of matter, so to first order we can write the diffuse background intensity from dark matter annihilation as

\[
\epsilon I_{\nu}^{\text{DM}} = \frac{m_\epsilon c^2}{4\pi} \int_0^{s_{\text{max}}} dz \frac{d\epsilon_*}{dz} n_{\text{DM}}(\epsilon_*, z).
\]

The spectral production rate of dark matter secondaries is written as

\[
\frac{\dot{n}_{\text{DM}}(\epsilon_*, z)}{c} \sim j_n n_{\text{DM}}^2(1+z)^6 \sigma_{\text{DM}} \delta(\epsilon_* - \epsilon_\chi),
\]
where $\epsilon_\gamma$ is the energy of secondary $\gamma$ rays or $\nu$ produced in dark matter annihilation, and $j_\gamma$ is the multiplicity of the secondaries. The maximum redshift $z_{\text{max}}$ represents the redshift where dark matter was created or fell out of equilibrium.

Hence

$$e L_\nu \propto \int_0^{z_{\text{max}}} dz \frac{e^{2 \delta (1 + z - \epsilon_\gamma)}}{(1 + z)^{5/2}} \propto (\epsilon/\epsilon_\gamma)^{-1/2}$$

(33)

for $\epsilon \lesssim \epsilon_\gamma/z_{\text{max}}$. A diffuse $\nu$ background from annihilation of dark matter particles with masses of $\sim 10$ GeV – TeV could peak near $10 - 100$ MeV, for $z_{\text{max}} \sim 10^4$. A component of the diffuse extragalactic $\gamma$-ray background in the 10 MeV – GeV range would be formed under the same circumstances as the annihilation $\gamma$ rays cascaded to photon energies where the universe becomes transparent to $\gamma \gamma$ pair production.

If $z_{\text{max}}$ corresponds, however, to a redshift where the temperature of the CMB corresponds to the dark matter particle energy, then this indirect signature of dark matter annihilation is probably not detectable. In any case, a residual photonic or $\nu$ signature from dark matter annihilation in the early universe will be associated with any assumed dark matter annihilation cross section, and this emission signature cannot exceed measured values or upper limits.

5 Discussion

By inferring source densities and event rates from astronomical observations (Fig. 1), fits can be made to statistical (e.g., redshift and size) distributions of high-energy sources detected with GLAST and other high-energy telescopes. A model that fits the distributions entails an imperative, for each source class, to show that the superpositions of radiations formed by the faint model sources below the detection limit do not overproduce the measured diffuse $\gamma$-ray background and upper limits to the $\nu$ background radiations. We illustrate the technique in what follows, first considering detection of quasi-isotropic cosmic-ray induced emissions from star-forming galaxies.

5.1 $\gamma$-rays and $\nu$ from Unbeamed Sources

Cosmic-ray induced emissions from extragalactic sources are weak [15,16], which must be the case in order to agree with the lack of high significance detections of $\gamma$ rays from star-forming galaxies without jets. Other than the LMC [17], which was observed with EGRET at a flux level consistent with that expected if cosmic rays were produced at a rate proportional to the star formation rate of the Milky Way, no unbeamed extragalactic high-energy radiation source has yet been detected with high confidence.

Normal, Starburst, and Infrared Luminous Galaxies. If cosmic-ray induced emissions are primarily responsible for the high-energy quasi-omni directional emissions from extragalactic sources, then the level of emission from the Milky Way can be appropriately scaled to estimate the expected flux levels of galaxies of different types. The $\gamma$-ray photon production rate from the Milky Way inferred from COS-B observations [18] is $N_\gamma \approx (1.3 - 2.5) \times 10^{42}$ ph($>100$ MeV) s$^{-1}$ implying a $>100$ MeV $\gamma$-ray luminosity from the Milky Way of $10^{39} L_{39}$ ergs s$^{-1}$, with $L_{39} = (0.16 - 0.32)$. Analysis using GALPROP Galactic cosmic-ray propagation model [20] indicates that, taking into account the GeV excess in the diffuse galactic emission observed with EGRET and using a larger model Milky Way halo, the $>100$ MeV $\gamma$-ray luminosity of the Milky Way is $10^{39} L_{39}$ ergs s$^{-1}$, with $L_{39} = (0.71 - 0.92)$. Some 90% of this emission is due to secondary nuclear production when cosmic rays collide with gas and dust in the Galaxy.

Approximating the integrated $>100$ MeV photon spectrum as a power law with a mean photon spectral index $= 2.4$ implies that the $\nu L_\nu$ spectrum of the Milky Way is

$$e L_{MW}(\epsilon) \approx 3.3 \times 10^{39} L_{39} \epsilon^{-0.4} \text{ ergs s}^{-1}$$

(34)

for $\epsilon = h\nu/m_e c^2 \gtrsim 200$ (i.e., $>100$ MeV), or $N(>100$ MeV) $\approx 10^{43} \text{ ph s}^{-1}$.

By scaling nearby galaxies according to their supernova rates, a simple estimate for the $\gamma$-ray and $\nu$ emissions can be made. For example, the supernova rate of Andromeda (M31), at a distance of $\approx 800$ kpc, is $\approx 1$ per century, compared to the rate of 2.5 every century in the Milky Way [15]. Thus the expected $\gamma$-ray photon flux from M31 should be at the level

$$\phi_{M31}(>100 \text{ MeV}) \approx \frac{1}{2.5} \frac{10^{43} \text{ ph s}^{-1}}{L_{39}(800 \text{ kpc})^2} \approx 0.9 \times 10^{-8} L_{39} \text{ cm}^{-2} \text{ s}^{-1},$$

(35)

for $\alpha_\nu = -0.4$, which would be significantly detected with GLAST. Pavlidou and Fields (2001) [15] perform a more detailed treatment of local group galaxies and predict that the $>100$ MeV integral photon flux from the SMC, M31, and M33 are at the levels of $1.7 \times 10^{-8}$, $1.0 \times 10^{-8}$, and $0.11 \times 10^{-8}$ ph ($>100$ MeV) cm$^{-2}$ s$^{-1}$, respectively. GLAST should therefore detect at least the SMC and M31, though its 1 year sensitivity of $\approx 0.4 \times 10^{-8}$ ph($>100$ MeV) cm$^{-2}$ s$^{-1}$ means that few other local group galaxies are likely to be detected. The difference between the simple-minded treatment presented here and their more detailed treatment is a consideration of the total target mass density of the different galaxies, and diffusion and escape of cosmic rays from the galaxy, which is especially important for the Magellanic Clouds.

By extrapolating the integrated diffuse galactic continuum emission from the Milky Way to TeV energies,
the integral number flux of $\gamma$ rays from a Milky-Way type galaxy at the distance $d$ is

$$\phi(>\epsilon) \approx 2 \times 10^{-13} \eta \epsilon_{39}^{-1.4} / d(\text{Mpc})^2$$

where the $\eta$ factor accounts for the different supernova rates and target densities for the galaxy under consideration, as well as the reduced number of $\gamma$ rays if the spectrum softens with energy. Because the imaging atmospheric Cherenkov telescopes HESS and VERITAS have sensitivities of $\approx 4 \times 10^{-13} \text{ph}(>300 \text{ GeV}) \text{ cm}^{-2} \text{ s}^{-1}$ for $\approx 50$ hour observations (see Fig. 2), M31, a northern hemisphere source (+41° declination), could be marginally detectable with VERITAS in long exposures, provided that the spectral GeV-TeV softening and reduction in sensitivity due to M31’s angular extent, $\approx 1^\circ$, are not too great.

The enhanced supernova rate in starburst galaxies such as M82 and NGC 253 at $\approx 3$ Mpc improve the prospects that they could be detectable with GLAST and ground-based Cherenkov telescopes [16]. In the inner starburst regions of these sources, interaction of cosmic rays with the strong stellar winds would produce GeV and TeV radiation [22]. These processes will also generate neutrinos, though it is unlikely that they will be detected with IceCube or a Northern Hemisphere km-scale neutrino telescope, as these detectors have a sensitivity comparable to EGRET in terms of fluence.

Torres (2004) [24] developed a detailed model of the nonthermal cosmic-ray production from the ultraluminous infrared galaxy (ULIRG) Arp 220 at $\approx 72$ Mpc. ULIRGs are the result of merging galaxies that drive large amounts of gas to the center of the system to form a dense gas disk, trigger a starburst, and possibly fuel a buried AGN. Because of their intense infrared emissions, Compton scattered radiations from cosmic ray electrons on the IR photons could additionally enhance the $\gamma$-ray fluxes. In spite of its large distance, Arp 220 is potentially detectable with GLAST and the ground-based $\gamma$-ray telescopes [24], because the dense clouds of target gas and increased cosmic ray confinement significantly increase the brightness of ULIRGs in comparison to expectations from a simple scaling to the Milky Way.

Clusters of Galaxies Nonthermal radiation will accompany the formation of collisionless shocks by merging clusters of galaxies during the merger of dark matter halos in the standard model for the growth of structure in a $\Lambda$CDM universe [25]. The available energy in the merger between a cluster of mass $M_1 = 10^{15} M_\odot$ and a smaller cluster of mass $M_2 = 10^{14} M_\odot$, initially separated by a distance of $r_1 = r_{\text{Mpc}}$ Mpc, is

$$\mathcal{E} \approx \frac{G M_1 M_2}{r} \approx 8 \times 10^{63} \frac{M_\odot}{r_{\text{Mpc}}} \text{ ergs} \ .$$

If only a very tiny fraction of this energy is dissipated in the form of nonthermal cosmic rays protons, then $\approx 10^{60}$ ergs of cosmic rays, which are effectively trapped in the cluster even for a weak, $\approx 0.1\mu$G, magnetic field, will be dissipated on the mean timescale for a nuclear collision with cluster gas. The thermal X-ray bremsstrahlung cluster emission shows that the thermal cluster matter density is $n_{th} \approx 10^{-3} \text{ cm}^{-3}$, so that the characteristic timescale for nuclear interactions is $t_{pp} \approx (n_{th} \sigma_{pp} c)^{-1} \approx 10^{18} \text{ s}$. Hence the bolometric nonthermal cluster luminosity from pion producing interactions is $L_{pp} \approx 10^{42} \text{ ergs} \text{ s}^{-1}$.

Fig. 2 shows Berrington’s calculations [26] of the predicted $\gamma$-ray emission from the Coma cluster of galaxies, using parameters appropriate to the recent merger that has taken place in the Coma cluster environment ($d \approx 100$ Mpc). Point-source sensitivity limits for VERITAS (which is comparable to the HESS sensitivity) are taken from Ref. [21], though the sensitivity may be degraded by Coma’s angular extent [28]. The predicted $\gamma$-ray emission falls below the EGRET sensitivity curve and the measured 2$\sigma$ upper limit of $3.81 \times 10^{-8} \text{ph}(>100 \text{ MeV}) \text{ cm}^{-2} \text{ s}^{-1}$ [27]. The results from the merging cluster model show that GLAST will significantly detect the non-thermal $\gamma$-rays from Coma to energies of several GeV. Furthermore, VERITAS could have a high confidence ( $\approx 5\sigma$) detection of Coma (at declination $+38^\circ$),

\footnote{A fuller discussion of neutrino sources will be given in my Madison proceedings for TeV/Particle Astrophysics II.}
depending on detail on the fraction of energy going into shocked cosmic-ray protons, the nonthermal nature of Coma’s hard X-ray spectrum, and the amount of nonthermal proton energy left over from previous merger events.

In addition to merger shocks, high Mach number accretion shocks at the periphery of a forming cluster can accelerate nonthermal particles [29]. The diffuse γ-ray background formed by intergalactic structure formation shocks from the calculations of Keshet et al. (2003) [30] is shown in Fig. 3. Gamma-ray emission has not yet been convincingly detected from clusters of galaxies [27], but calculations like this indicate that clusters of galaxies are likely to be the next established class of extragalactic sources of high-energy radiation.

**Diffuse Intensity from Star-Forming Galaxies** We can use eq. [28] to calculate the diffuse intensity from star-forming galaxies by normalizing to the density and nonthermal γ-ray luminosity of $L_*$ galaxies like the Milky Way. Fits of galaxy surveys to the Schechter luminosity function imply that the density of $L_*$ galaxies is $n_s = 0.016h^3$ Mpc$^{-3}$ ≈ 1/(170 Mpc$^{-3}$) [31]. Employing a mono-luminosity galaxy luminosity function, $\epsilon I_\gamma (\epsilon_*, z) = n_s \Sigma_\epsilon (z) \epsilon_* L_*(\epsilon_*)$, and eq. [28] becomes, using eq. [34],

$$\epsilon I_\gamma (\epsilon_*) = \frac{c}{4\pi} \int_0^\infty \frac{d\epsilon_\gamma}{d\epsilon_\gamma} \frac{\epsilon^2 \epsilon_\gamma (\epsilon_*, z)}{1+z} \approx 4 \times 10^{-7} \times (\frac{\epsilon}{200})^{-0.4} \int_0^\infty \frac{\Sigma_\epsilon (1+z)^{-2.4} \epsilon^7}{\sqrt{\Omega_m (1+z)^3 + \Omega_k}} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}. \quad (38)$$

Using the star formation rate function of Ref. [7], the integral in eq. [38] is easily performed to give a value of 2.14, so that $\epsilon I_\gamma (\epsilon_*) \approx 8.7 \times 10^{-7}[\epsilon_\gamma/(100 \text{ MeV})]^{-0.4} \text{ GeV cm}^{-2} \text{s sr}^{-1}$. This result is in good agreement with the more detailed treatment of the “guaranteed γ-ray background” by Pavlidou and Fields (2002) [32], plotted in Fig. 3. The upper curve is scaled to a dust-corrected star formation rate, and the lower curve stops the integration at $z = 1$. Also shown is the intensity of starburst galaxies estimated from a radio/FIR correlation [33].

**Extragalactic Pulsar Emissions** Using SAS-2 data for the diffuse galactic γ-ray emission and EGRET data for pulsars, the analysis of Ref. [34] shows that the total $\gtrsim 100$ MeV flux of diffuse radiation from the Milky Way is $\approx 1.5 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$, and the combined flux of the 6 brightest EGRET pulsars is $\approx 1.35 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$. The modeling in that paper shows that the superposition of diffuse fluxes of unresolved pulsars is at the level of $\sim 1.2 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$. Thus total pulsar emissions make up as much as 20% of the total galactic γ-ray flux in star-forming galaxies like the Milky Way.

The apparently diffuse emissions from pulsars in galaxies throughout the universe is then, to first order, at the level of $\approx 20\%$ and proportional to the star formation history of the universe. A number of important effects must be considered for more accurate estimates of the extragalactic diffuse pulsar flux at different γ-ray energies, most obviously being the harder pulsar spectrum (compared to the cosmic-ray induced emissions) at energies up to the pulsar cutoff energies between $\approx 1 – 100$ GeV [35,36]. Of great interest is to accurately measure the high-energy pulsar spectral cutoffs with GLAST, which can be included in a more complete model for the pulsar contribution to the diffuse galactic background. Unfortunately, GLAST would not be sensitive to detect Milky-Way like γ-ray pulsars from nearby galaxies. Placing the Crab pulsar at 1 Mpc would yield a $\sim 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ isotropic flux.

5.2 γ-rays and ν from Beamed Sources

The evidence from EGRET and Whipple shows that beamed GRBs and blazars are the brightest extragalactic high-energy γ-ray sources, and that isotropically emitting sources will be difficult to detect except in a few cases, as just demonstrated.

**Microquasars** One class of beamed source that has not yet been detected from beyond the Galaxy is the microquasar class, even though some of the ultraluminous X-ray sources seen in nearby galaxies could be microquasars with their jets oriented towards us [37]. Presently only high-mass microquasars are known sources of GeV and TeV radiation, and the evidence of associations of...
\gamma\text{-ray sources with low-mass systems is weak. The established cases of \gamma\text{-ray emitting microquasars are LS 5039, associated with an unidentified EGRET source [38] and unambiguously detected with HESS [39], and LSI +61 303, whose orbital modulation has been recently demonstrated with the MAGIC telescope [40]. Models for microquasars do not require large bulk Lorentz factors \Gamma of the plasma outflow in microquasar jets [41], and superluminal motion observations generally reveal microquasar Doppler factors \lesssim 2. The small sample leaves open the possibility that \Gamma could exceed a few, which would make possible the detection of microquasars from distant galaxies. Using eq. (19) and the threshold expression \delta^2 D q f_\nu / d^2 \gtrsim f_\nu \gtrsim 10^{-12} \text{ergs cm}^{-2} \text{s}^{-1}, we find that for a flat \nu F_\nu spectrum (\alpha_v = 2) that \delta^2 D \gtrsim 6 (d/\text{Mpc})^2 for a Chandrasekhar mass compact object and a bolometric factor \lambda_b = 10. Thus, Doppler factors of only a few or greater are needed in order to detect microquasars from galaxies at distances \gtrsim 1 \text{Mpc.}

**Gamma Ray Bursts** A detailed treatment of the statistics of GRBs is given in Ref. [6]. We can use those results and eq. (25) to estimate the diffuse \gamma\text{-ray background from GRBs. To simplify the results, we consider all GRBs, including those above threshold, and approximate the GRB spectrum as a flat \nu F_\nu spectrum to the highest \gamma\text{-ray energies. The diffuse \gamma\text{-ray background intensity is then given by

\[ \epsilon I_{GRB} \equiv \frac{c \dot{n}_{GRB} \epsilon_{GRB}}{4\pi \lambda_0 H_0} \int_0^\infty \frac{\Sigma_{GRB}(z)}{(1 + z)^2} \, dz. \] (39)

For a local GRB event rate \dot{n}_{GRB} = 10 \dot{n}_{10} \text{Gpc}^{-3} \text{yr}^{-1},

\[ \epsilon I_{GRB} \equiv \frac{3 \times 10^{-9} \lambda_{10}}{\lambda_{10}} \int_0^\infty \frac{d(1 + z)^{-2} \Sigma_{GRB}(z)}{\sqrt{\Omega_m(1 + z)^3 + \Omega_A}} \, dz, \] (40)

in units of GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\).

Using star formation rates 5 and 6 that allow the redshift and jet opening angle distributions to be fit [6] gives the diffuse intensity from GRBs shown in Fig. 3 which is a small fraction of the diffuse \gamma\text{-ray background.

**Blazars** EGRET and GLAST data on blazars can be analyzed with models that jointly fit the redshift and flux size distribution and predict the level of the extragalactic \gamma\text{-ray background (GRB) [9,5]. The diffuse intensities of unresolved FSRQ (dashed) and BL Lac (dotted) blazars, and the total AGN contribution (shaded), are shown in Fig. 3 [5]. The ranges correspond to sensitivities \phi_{-8} = 25 and \phi_{-8} = 12.5. The BL Lac objects and FSRQs, including emissions from misaligned radio galaxies, contribute at the \sim 2 – 4% and \sim 10 – 15% levels, respectively, to the total EGRB [19] near 1 GeV.

The sum of the different contributions in Fig. 3 at \sim 1 GeV is at about the level of the total diffuse extragalactic \gamma\text{-ray emissions measured with EGRET [19]. Soft blazar sources, and softer than modeled diffuse cosmic ray emissions from normal galaxies, could account for the residual emissions between \sim 50 \text{MeV} – 1 \text{GeV}. New hard \gamma\text{-ray source populations are apparently required at \gtrsim 10 \text{GeV}, which would include cascade emission from UHE electromagnetic cascades with photons of the EBL.

### 6 Summary and Conclusions

It will be of considerable interest when GLAST or a TeV telescope detects M31 or another galaxy of the local group, or a starburst or IR luminous galaxy. The measured flux will give a valuable check on the efficiency of cosmic ray production as a function of galactic star formation activity, and will provide a further normalization, after the Milky Way and the LMC, of the contribution of star forming galaxies to the \gamma\text{-ray background.

GLAST will provide large statistical samples on at least two source classes: GRBs and blazars. There are good reasons to think that GLAST will detect star forming galaxies and clusters of galaxies. Although the sensitivity to extended sources is degraded in TeV telescopes, the Coma cluster is near the threshold for detection, depending on its nonthermal X-ray spectrum, but M31 would require fortunate spectral and spatial emissions to be detected.

For GRBs and blazars, there are already fundamentally interesting questions about the evolution of the source rate densities and change in properties of relativistic jet sources through cosmic time. For \gamma\text{-ray emitting BL Lac objects, positive source evolution (more sources at late times) and negative luminosity evolution (sources brighter in the past) explains the statistical distributions from EGRET [5]. Detection of blazars to high redshift, z \gtrsim 5, is expected with GLAST. It will be interesting to see if GLAST LAT-detected GRBs are peculiar in their properties compared to long-duration GRBs found by burst detectors with \sim 100 \text{keV} triggers.

The EGRB is probably a composite of many source classes (Fig. 3), which can best be established by identifying individual sources with better sensitivity detectors. The contribution of beamed to unbeamed sources, after subtracting known sources, is limited by the \gamma\text{-ray statistical excursions of the EGRB measured with GLAST. GLAST will monitor blazar and GRB flaring with its \sim 2 \text{sr} field of view, and rapidly slewing instruments like MAGIC may soon discover the first VHE, \gtrsim 10 \text{GeV}, GRB. But a wide field-of-view ground-based \gamma\text{-ray telescope, like HAWC or the next generation TeV telescopes, will have the best chance to monitor TeV \gamma\text{-ray transients for follow-up observations. Improved statistical analyses of \gamma\text{-ray and particle astronomy projects will tell us the composition of the unresolved residual \gamma\text{-ray emission, and if there are room for more source classes, such as dark matter emissions, anomalous microquasars or odd classes of \gamma\text{-ray emitting objects yet to be discovered.}
Acknowledgements I would like to thank the organizers, Josep M. Paredes, Olaf Reimer, and Diego F. Torres, for the kind invitation to speak at this conference, and for the opportunity to visit the beautiful city of Barcelona. I would also like to thank A. Atotyan, T. Le, and V. Vassiliev for discussions, and to Dr. Vassiliev for correcting an error in the draft version. This work is supported by the Office of Naval Research and a GLAST Interdisciplinary Scientist grant.

References

1. Halzen, F.: Astroparticle Physics with High Energy Neutrinos: from AMANDA to IceCube. (astro-ph/0602132)
2. Böttcher, M.: Modeling the Emission Processes in Blazars. These proceedings (astro-ph/0608713) (2006)
3. Peebles, P. J. E.: Principles of Physical Cosmology. Princeton Series in Physics. Princeton University Press, Princeton, NJ (1993)
4. Spergel, D. N., et al.: First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters. Astrophys. J. Supp., 148, 175–194 (2003)
5. Dermer, C. D.: Statistics of Cosmological Black Hole Jet Sources: Blazar Predictions for GLAST. Astrophys. J., submitted, astro-ph/0605402 (2006)
6. Le, T., Dermer, C. D.: Statistics of Gamma-Ray Bursts in the Swift Era. Submitted to the Astrophys. J. (2006)
7. Hopkins, A. M., Beacom, J. F.: On the normalisation of the cosmic star formation history, Astrophys. J., 651, 142 – 154 (2006)
8. Dermer, C. D., Atoyan, A.: Nonthermal Radiation Processes in X-Ray Jets. Astrophys. J., Lett., 611, L9-L12 (2004)
9. Mücke, A., Pohl, M.: The contribution of unresolved radio loud AGN to the extragalactic diffuse gamma-ray background. MNRAS, 312, 177–193 (2000)
10. Böttcher, M., Dermer, C. D.: An Evolutionary Scenario for Blazar Unification. Astrophys. J., 564, 86–91 (2002)
11. Sanders, D. B.: The Cosmic Evolution of Luminous Infrared Galaxies: from IRAS to SCO, SCUBA, and SIRTF. Adv. Space Res., 34, 535-545 (2004)
12. Murase, K., Nagataki, S.: High energy neutrino emission and neutrino background from gamma-ray bursts in the internal shock model. Phys. Rev. D, 73, 063002 1-14 (2006)
13. Dermer, C. D., Holmes, J. M.: Ultra-high energy cosmic rays, gamma-rays and neutrinos from GRBs, in preparation (2006)
14. Sigl, G.: Ultra High Energy Cosmic Radiation: Experimental and Theoretical Status, astro-ph/0609257 (2006)
15. Pavlidou, V., Fields, B. D.: Diffuse Gamma Rays from Local Group Galaxies. Astrophys. J., 558, 63-71 (2001)
16. Torres, D. F., Reimer, O., Domingo-Santamaria, E., Digel, S. W.: Luminous Infrared Galaxies as Plausible Gamma Ray Sources for the Gamma-Ray Large Area Space Telescope and the Imaging Atmospheric Cerenkov Telescopes. Astrophys. J. Lett., 607, L90-L102 (2004)
17. Sreekumar, P., et al.: Observations of the Large Magellanic Cloud in high-energy gamma rays. Astrophys. J. Lett., 400, L67-L70 (1992)
18. Bloemen, J. B. G. M., Blitz, L., Hermsen, W.: The radial distribution of galactic gamma-rays. I - Emissivity and extent in the outer galaxy. Astrophys. J., 279, 136–143 (1984)
19. Sreekumar, P., et al.: EGRET Observations of the Extragalactic Gamma-Ray Emission. Astrophys. J., 494, 523–534 (1998)
20. Strong, A. W., Moskalenko, I. V., Reimer, O. 2000: Diffuse Continuum Gamma Rays from the Galaxy. Astrophys. J., 537, 763–784 (1984)
21. Weekes, T. C., et al.: VERITAS: the Very Energetic Radiation Imaging Telescope Array System. Astroparticle Physics, 17, 22-243 (2002)
22. Romero, G. E., Torres, D. F.: Signatures of Hadronic Cosmic Rays in Starbursts? High-Energy Photons and Neutrinos from NGC 253. Astrophys. J. Lett., 586, L33-L36 (2003)
23. Domingo-Santamaria, E., Torres, D. F.: High energy gamma-ray emission from the starburst nucleus of NGC 253. Astroparticle Physics, 144, 403–415 (2005)
24. Torres, D. F.: Theoretical Modeling of the Diffuse Emission of Gamma Rays from Extreme Regions of Star Formation: The Case of Arp 220. Astrophys. J., 617, 966–986 (2004)
25. Bykov, A. M., Bloemen, H., Uvarov, Y. A.: Nonthermal emission from clusters of galaxies. Astronomy and Astrophys., 362, 886-894 (2000)
26. Berrington, R. C., Dermer, C. D.: Gamma Ray Emission from Merger Shocks in the Coma Cluster of Galaxies. astro-ph/0407278 (2004)
27. Reimer, O., Pohl, M., Sreekumar, P., Mattson, J. R.: EGRET Upper Limits on the High-Energy Gamma-Ray Emission of Galaxy Clusters. Astrophys. J., 588, 155-164 (2003)
28. Gabici, S., Blasi, P.: On the detectability of gamma rays from clusters of galaxies: mergers versus secondary infall. Astroparticle Physics, 20, 579-590 (2004)
29. Ryn, D., Kang, J., Hallman, E., Jones, T. W.: Cosmological Shock Waves and Their Role in the Large-Scale Structure of the Universe. Astrophys. J., 593, 599-610 (2003)
30. Keshet, U., Waxman, E., Loeb, A., Springel, V., Hernquist, L.: Gamma Rays from Intergalactic Shocks. Astrophys. J., 585, 128–150 (2003)
31. Binney, J., Merrifield, M.: Galactic Astronomy. Princeton University Press, Princeton, N. J. (1998)
32. Pavlidou, V., Fields, B. D.: The Guaranteed Gamma-Ray Background. Astrophys. J. Lett., 575, L5-L8 (2002)
33. Thompson, T. A., Quataert, E., Waxman, E.: The Starburst Contribution to the Extragalactic Gamma-Ray Background. Astrophys. J., submitted (astro-ph/0606665) (2006)
34. Sturmer, S. J., Dermer, C. D.: Statistical Analysis of Gamma-Ray Properties of Rotation-powered Pulsars. Astrophys. J., 461, 872-883 (1996)
35. Thompson, D. J., Harding, A. K., Hermen, W., Ulmer, M. P.: Gamma-Ray Pulsars: The Compton Observatory Contribution to the Study of Isolated Neutron Stars. Proceedings of the Fourth Compton Symposium, AIP, Woodbury, N.Y., 410, 39 – 58 (1997)
36. Strong, A. W.: Source population synthesis and the Galactic diffuse gamma-ray emission. These proceedings (astro-ph/0609359) (2006)
37. Georganopoulos, M., Aharonian, F. A., Kirk, J. G.: External Compton emission from relativistic jets in Galactic black hole candidates and ultraluminous X-ray sources. Astronomy and Astrophys., 388, L25-L28 (2002)
38. Paredes, J. M., Martí, J., Ribó, M., Massi, M.: Discovery of a High-Energy Gamma-Ray-Emitting Persistent Microquasar. Science, 288, 2340–2342 (2000)
39. Aharonian, F., et al.: Discovery of Very High Energy Gamma Rays Associated with an X-ray Binary. Science, 309, 746–749 (2005)
40. Albert, J., et al.: Variable Very-High-Energy Gamma-Ray Emission from the Microquasar LS I+61 303. Science, 312, 1771–1773 (2006)
41. Bosch-Ramon, V., Romero, G. E., Paredes, J. M.: A broadband leptonic model for gamma-ray emitting microquasars. Astronomy and Astrophys., 447, 263-276 (2006)