Observational Gamma-ray Cosmology

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Abstract. We discuss how measurements of the absorption of gamma-rays from GeV to TeV energies via pair production on the extragalactic background light (EBL) can probe important issues in galaxy formation. Semi-analytic models (SAMs) of galaxy formation, based on the flat LCDM hierarchical structure formation scenario, are used to make predictions of the EBL from 0.1 to 1000 microns. SAMs incorporate simplified physical treatments of the key processes of galaxy formation – including gravitational collapse and merging of dark matter halos, gas cooling and dissipation, star formation, supernova feedback and metal production. We will summarize SAM successes and failures in accounting for observations at low and high redshift. New ground- and space-based gamma ray telescopes will help to determine the EBL, and also help to explain its origin by constraining some of the most uncertain features of galaxy formation theory, including the stellar initial mass function, the history of star formation, and the reprocessing of light by dust. On a separate topic concerning gamma ray cosmology, we discuss a new theoretical insight into the distribution of dark matter at the center of the Milky Way, and its implications concerning the high energy gamma rays observed from the Galactic center.

INTRODUCTION

The main process that removes high energy gamma rays en route from remote active galactic nuclei (AGN) to our detectors is absorption via $\gamma\gamma \rightarrow e^+ e^-$ as the gamma rays move through the evolving extragalactic background light (EBL).

From the earliest work on the cold dark matter (CDM) theory of structure formation in the universe (Blumenthal et al. 1984), semianalytic models (SAMs) have been used to estimate the properties of the population of galaxies that will form in a given cosmological model. These models typically treat galaxy formation and evolution based on simple approximations such as spherical collapse, but they do treat accurately the most secure aspects of the theory, in particular the CDM power spectrum of fluctuations. As dark matter theory has progressed, it became possible to base the calculation of galaxy formation on the approximate merging history of a population of dark matter halos calculated using Monte Carlo methods (White & Frenk 1991, Somerville & Kolatt 1999), and this has been the main method used in SAMs (e.g. Kauffmann, White, & Guiderdoni 1993; Somerville & Primack 1999; Cole et al. 2000).\footnote{Modern high-resolution simulations permit the calculation of structural merger trees which characterize the radial profiles and angular momenta of the merging dark matter halos (e.g. Wechsler et al. 2002), and we are now doing SAMs based on this. This is important for predicting the dependence of galaxy properties on environment, but the results for large galaxy populations are similar to those of the simpler} We calculated the emission...
FIGURE 1. Luminosity Density vs. Wavelength in the Nearby Universe. The black curve is the prediction of our current Semi-Analytic Model (SAM); the points are observational data.

of EBL by the entire evolving galaxy population initially using even simpler Press-Schechter (1974) models (MacMinn & Primack 1996), and then using state-of-the-art SAMs and taking into account the effects of dust, which obscures light emitted in starbursts driven by galaxy mergers, and reradiates the energy in the far infrared (Primack, Bullock, Somerville, & MacMinn 1999; Primack, Somerville, Bullock, & Devriendt 2001). In earlier work, it was necessary to consider several possible cosmologies, but the fundamental cosmological parameters have now been determined with remarkable accuracy based on the cosmic microwave background and the large scale distribution of galaxies at low redshift and of large low-density gas clouds of gas at redshift \( z \sim 3 \)\(^2\) (e.g. Spergel et al. 2003, Tegmark et al. 2004, Seljak et al. 2004), giving results that are compatible with all other available cosmological data (reviewed in Primack 2004). As a

\(^{2}\) These gas clouds are responsible for what is known as the Lyman alpha forest of absorption lines in quasar spectra.

Monte Carlo calculations used here.
result, in the present paper we just consider the now-standard LCDM cosmology with \( \Omega_{\text{matter}} = 0.3, \Omega_{\Lambda} = 0.7, \) Hubble parameter \( h = 0.7, \) and normalization \( \sigma_8 = 0.9. \)\(^3\)

**IMPLICATIONS FOR GAMMA-RAY ATTENUATION**

In addition to the greatly increased precision and confidence in the cosmological parameters, the main thing that has changed in calculating the EBL from SAMs is our knowledge about the luminosity function of galaxies, i.e. the number density of galaxies as a function of their luminosity. As a result of the agreement of the three large surveys of the nearby universe, 2MASS (Cole et al. 2001), 2dF (Norberg et al. 2002), and SDSS (Blanton et al. 2003), we now know the local luminosity density with unprecedented

\(^3\) Of these parameters, the only one uncertain enough to be a concern is \( \sigma_8. \) We have adopted \( \sigma_8 = 0.9 \) here because this leads to the early ionization of the universe indicated by the WMAP large-angle polarization, which would require exotic sources if the value of \( \sigma_8 \) were significantly lower (see e.g. Somerville, Bullock, & Livio 2003).
Gamma-ray Attenuation Edge. Each curve shows the redshift where the predicted attenuation as a function of gamma-ray energy is $e^{-1/2}$, $e^{-1}$, $e^{-2}$, $e^{-3}$, and $e^{-5}$.

precision in optical and near-infrared wavebands – see Figure 1. The key parameters in SAMs, those that govern the rate of star formation and of supernova energy feedback and metallicity yield, are adjusted to fit local galaxy data. The fact that this can be done well is shown by the good agreement between the curves in Figure 1 (predictions from our current favorite SAM) and the data from the UV to the far-IR. However, the optical luminosity density is lower than the best estimates of a few years ago, which is the main reason that our EBL curves in Figure 2 have come down across the spectrum compared to our earlier estimates.

Because the data now determine the local luminosity density in the optical band rather precisely, and because our collisional starburst SAM appears to do well at accounting for galaxy observations at optical wavelengths at higher redshifts (Somerville, Primack, Faber 2001, whose predictions were shown to agree with the GOODS survey data out to redshift $z = 6$ by Giavalisco et al. 2004), we think that the EBL in Figure 2 is probably pretty reliable in the optical and near-IR. The main uncertainty that we are aware of concerns the high near-IR (1-3 µm detections shown as upward pointing triangles in Figure 2. We are implicitly discounting these detections (e.g. Matsumoto et al. 2000, Wright 2004) because the systematic errors may not be fully represented by the error bars shown, and there is no known nearby source. However, an interesting proposed source is redshifted Lyman $\alpha$ radiation from early galaxies at redshifts $z \sim 9 - 13$ whose shorter wavelength radiation may have been responsible for the early ionization of the universe indicated by the WMAP polarization data (Salvaterra & Ferrara 2003, Magliocchetti et al. 2003). It may be possible to test this idea with new near-IR data (cf. Cooray et al. 2004) and also through the predicted increased absorption of $\sim 1$ TeV gamma rays from...
lower is therefore good news for the new generation of low energy threshold gamma ray detectors, including HESS, MAGIC, CANGAROO III and VERITAS atmospheric Cherenkov telescopes (ACTs), and the AGILE and GLAST gamma-ray satellites which are scheduled to be launched in 2005 and 2007. As gamma-ray telescopes look at lower energy gamma rays, they can see out to higher redshifts with less attenuation than previously predicted. This is shown in Figure 3, which shows curves representing varying degrees of attenuation (in powers of $e$) predicted for gamma rays travelling through the evolving radiation field corresponding to the EBL from our current SAM outputs, shown in Figure 4.

Figure 5 shows the implications of our current models for attenuation of the five well-characterized extragalactic gamma-ray sources, whose redshifts range from $z = 0.031$ to $z = 0.129$. The predicted and observed attenuation is rather mild for the nearest sources, Mrk 421 and Mrk 501 at $z = 0.031$ and $0.034$. It is only for the most distant TeV blazar H1426+428 at $z = 0.129$ that the observations (Aharonian et al. 2003, Costamante et al. 2004a) appear to support the shape of the predicted attenuation. Comparing available data on four blazars with the models, Costamante et al. (2004b) conclude that the observed attenuation is generally consistent with our theoretical expectations. Of course data with smaller error bars would be most welcome, and this should be forthcoming distant blazars such as 1ES 1426+428, which may disfavor it (cf. Costamante et al. 2004b).
FIGURE 5. Gamma-ray Attenuation vs. Gamma-ray Energy. The predicted attenuation is shown by the upper curves for sources at the redshifts of well studied blazars, and by the lower curves for sources at higher redshifts.

soon with the larger and more sensitive new ACTs now coming into operation.

THEORETICAL SUCCESSES AND FAILURES

There are two basic approaches to predicting the EBL, and thereby predicting gamma-ray attenuation as a function of source redshift and gamma-ray energy. The old approach of “backward models,” still followed by some, has been to start with the existing galaxy population and to model the luminosity evolution of these galaxies backward in time. There are great difficulties in principle with this approach. The EBL data shown in Fig. 2 indicate that the total energy in far-IR radiation is comparable to that in the optical and near-IR. However, the Milky Way, like most nearby galaxies, radiates much more of its energy in the optical and near-IR than the far-IR. Since most of the far-IR light must therefore have been radiated at higher redshifts, it has been diluted by a factor of \((1 + z_{\text{emission}})^{-1}\) by the expansion of the universe. It follows that radiation by higher-redshift galaxies must have been very different from that of nearby galaxies, with a much larger fraction of the light emitted in the far-IR. Backward evolution models are further compromised by the likelihood that such intense far-IR emission has often been triggered by galaxy mergers, so that it becomes increasingly difficult to model the galaxy.
population at increasing redshift by evolving the currently existing galaxies backward.

“Forward evolution,” the approach we follow, is based on assuming a fundamental theory of cosmology and galaxy formation. A decade ago this may have appeared to be a highly speculative approach, but it has now become much more plausible since we now know that all available data on large and intermediate scales is in spectacular agreement with the LCDM model. And as Fig. 1 shows, a modern LCDM-based SAM can account very successfully for the nearby luminosity density. Reasonable modifications (Somerville et al., in prep.) can also allow SAM models to account for detailed features of the galaxy population, such as the bimodality in galaxy colors and other properties observed at both low redshift (e.g. Kauffmann et al. 2003) and out at least to redshift $z \approx 1$ (e.g. Bell et al. 2004). However, SAM models and simulations have not yet been able to account for the bright far-IR galaxies observed by SCUBA and other instruments.
including ISO and Spitzer.\textsuperscript{5} This is shown by Figures 7 and 8. Figure 7 shows that three currently popular SAM approaches and the latest hydrodynamical simulations (Hernquist & Springel 2003) both lead to predictions for the evolution of the density of star formation vs. redshift which agree with the optical data but not with the star formation indicated by the SCUBA observations at 850 $\mu$m at $z \approx 2$ and the more uncertain observations at $z \approx 4$.\textsuperscript{6} Figure 8 shows that the discrepancy between our SAM predictions for number counts and observations is worst for the bright SCUBA data. Thus, while our SAM predictions appear to be in good agreement with optical data both nearby and at high redshift, we are clearly underestimating the contribution of galaxies at $z \gtrsim 0.7$ to the far-IR and perhaps also the mid-IR. It follows that our attenuation curves in Figs. 3 and 5 are likely to be reliable for gamma-ray energies $\lesssim 1$ TeV, but they probably underestimate the attenuation at higher gamma-ray energies.

\textsuperscript{5} A recent paper (Baugh et al. 2004) presents a SAM which can account for SCUBA sources by assuming that starbursts have a “top-heavy” stellar initial mass function, in which most of the stellar mass goes into high-mass stars. This would of course imply a very high supernova rate, and it remains to be seen whether this is consistent with observed properties of such galaxies.

\textsuperscript{6} See e.g. Chary & Elbaz (2001) for a similar conclusion regarding the star formation indicated by the ISO 15 $\mu$m data at $z \approx 0.7$ (cf. Chary et al. 2004).
PROSPECT

We are now writing a series of papers on results from our current SAM models, including revised versions of the EBL and gamma-ray attenuation results presented here. T. J. Cox and Patrik Jonsson, who finished their PhDs with Primack in September 2004 (Cox 2004, Jonsson 2004), have been doing an extensive program of high-resolution hydrodynamic simulations of galaxy interactions including the effects of dust absorption, scattering, and reradiation. On a longer timescale, but still within approximately the next year, we plan to incorporate these new insights into improved SAM models which we hope will do a better job than our current ones of accounting for the bright far-IR emission from galaxies.

DARK MATTER ANNIHILATION AT THE MILKY WAY CENTER?

In this last section, we turn to a different topic. In a recent paper, Gnedin & Primack (2004) considered the effect of the scattering of dark matter particles by the star cluster surrounding the supermassive black hole at the center of the Galaxy. They showed using a Fokker-Planck treatment that this results in a unique radial density profile proportional to $r^{-3/2}$, which will extend from $\sim 10^{-4}$ pc from the black hole (where the density is cut off due to annihilation of the dark matter, assumed to be weakly interacting massive particles, WIMPs) to $\sim 2$ pc. Since the annihilation rate is proportional to the square of the dark matter density, the cuspy density profile implies that the annihilation peaks at the location of the black hole. The high-energy gamma-ray signal from the Galactic center observed by H.E.S.S. (Aharonian et al. 2004, Horns et al. 2004) appears to have this sort of point-like character. This interpretation of the signal implies a WIMP mass of $\sim 20$ TeV, which is much higher than was expected on the basis of common supersymmetric models, but not obviously inconsistent. WIMP annihilation implies a characteristic cut off in the energy spectrum, and the data taken in 2004 with the full four-telescope H.E.S.S. array may also have adequate angular resolution to help discriminate this interpretation from alternative ones. Unfortunately, while the radial profile of the central dark matter density is known, its magnitude is not – since there are processes that enhance the density and other processes that diminish it, and none of these processes are understood well enough to permit reliable calculations. Thus if dark matter annihilation is not discovered at the Galactic center the implications for WIMPs may not be clear.

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