The transparency of the universe for very high energy gamma-rays

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The propagation of very high energy gamma-rays ($E > 100$ GeV) over cosmological distances is suppressed by pair-production processes with the ubiquitous extra-galactic soft photon background, mainly in the optical to near infra-red. The detailed spectroscopy of gamma-ray emitting blazars has revealed the signature of this absorption process leading to a meaningful measurement of the background photon field which is linked to the star-forming history of the universe. Deviations from the expected absorption have been claimed in the past. Here the status of the observations is summarized, an update on the search for the persisting anomalous transparency is given and discussed.

Keywords: MG14 Proceedings; high energy gamma-rays; background light; axions; axion-like particles, Lorentz invariance violation

1. Introduction and Context

The current generation of ground based imaging air Cherenkov telescopes has been sufficiently sensitive to discover astrophysical gamma-ray emission in the energy range above 100 GeV from currently $> 60$ active galactic nuclei (at the time of writing). The current record-holder as the most distant known gamma-ray source is observed at a red shift of $z = 0.944$. At this distance, the effect of pair production becomes important at energies above 100 GeV leading to the energy-dependent absorption of the primary beam (see Fig. 1). For objects at a red shift of 0.01, absorption is only of relevance at photon energies above 10 TeV.

This energy-dependent effect is well known. However, the uncertainties (by roughly a factor of two) on the amount of background light translate directly to uncertainties on the predicted optical depth $\tau$, which widely changes the resulting attenuation $\exp(-\tau)$.

Additional effects related to the production of secondary photons in inter-galactic cascades may have an impact on the observed energy spectrum. The observable (secondary) flux depends on the intervening magnetic field and plasma properties which can lead to quenching of the cascade.

Finally, phenomena beyond the standard model of particle physics could modify this picture in characteristic ways (see below).

Before turning to the modifications of the pair production processes, I summarize the current state of knowledge on the extra-galactic background light (EBL) drawn from the imprint of absorption in the observed gamma-ray spectra (for an extended review, see also [5]).
2. Measurement of the Extra Galactic Background Light (EBL)

The direct observation of the extra galactic background light (EBL) is strongly affected by the dominating foreground emission from re-processed light in the interplanetary and interstellar medium (see e.g., [6]). The indirect approach to infer the amount of EBL present in the universe through the energy dependent imprint of absorption in gamma-ray spectra does not suffer from this uncertainty. Furthermore, it is in principle possible to follow the evolution of the EBL by measuring sources at various red shifts.

While in the past, the observed spectra were not determined with sufficient accuracy to derive the amount of absorption, current measurements of various bright sources (predominantly during flaring episodes,[7]), as well as the combination of available source spectra have been used to estimate the absorption and subsequently provide a measure of the amount of EBL present.[5]

Intrinsic to these analyses is however the ignorance of the intrinsic source spectra which is leading to systematic uncertainties on the reconstructed EBL. The assumption used, e.g., that the source spectrum is a power-law, may be over-simplifying: specifically for source spectra observed during flaring episodes, transient spectral components may be present at narrow energy intervals.[9] Combining the observations with lower-energy measurements with the pair-production telescope Fermi-LAT provides additional information on the un-absorbed energy spectrum and the presence of a spectral cut-off.

An interesting feature of the intrinsic spectra is an apparent dependence with red shift: the intrinsic source spectra show a hardening with increasing red shift which is not obviously linked with source characteristics. This trend is also present in a recent analysis,[8] and has been pointed out already in previous works.[10,11] The apparent hardening of the gamma-ray spectra with increasing red shift could be explained by mixing photons with a light pseudoscalar boson.[10] Additional studies indicate that the excess emission is mostly present in the optically thick part of the spectrum.[13]

3. Indications for anomalous transparency: An update

The claim of an indication for anomalous transparency (pair production anomaly)[13] has recently been shown to (mostly) disappear,[5] when increasing the data set and using an EBL derived from gamma-ray spectroscopy itself. The initial search for an anomalous transparency was based upon a flux ratio which is sensitive to excess emission when comparing the extrapolated energy spectrum with the observed value.[13]

Here, we introduce a new approach to characterise the spectral shape for different values of optical depth.

The analysis is based upon the so-called gamma-ray cosmology sample of blazars with known red shift.[5] Instead of using the power-law index determined from the spectrum observed at small optical depth to compare with the measured values at
large optical depth, a local measurement of the observed logarithmic slope $\alpha_i$ between two differential flux measurements $F_i(E_i)$ and $F_{i+1}(E_{i+1})$ ($E_{i+1} > E_i$) is used:

$$\alpha_i = \frac{\ln(F_{i+1}) - \ln(F_i)}{\ln(E_{i+1}) - \ln(E_i)},$$

(1)

such that the intrinsic logarithmic slope $\alpha'_i$ is given by

$$\alpha'_i = \alpha_i + \Delta_i(z),$$

(2)

with

$$\Delta_i(z) = \frac{\tau_{i+1}(z) - \tau_i(z)}{\ln(E_{i+1}) - \ln(E_i)},$$

(3)

where $\tau_i = \tau(E_i, z)$ is calculated according to an EBL model of choice.

Flux points with low statistical significance (and potentially large flux bias), i.e., which differ by less than 1.5 times the flux uncertainty from a zero value are excluded from the sample. An ad hoc flux bias correction has been applied to the remaining flux points, where the flux $F$ with uncertainty $\sigma_F$ is corrected in the following way:

$$F_{\text{cor}} = F \left[ 1 + \left( \frac{F}{\sigma_F} \right)^\zeta \right]^{-1},$$

(4)

with $\zeta \approx -2.5$ derived from a simple toy Monte Carlo assuming purely Gaussian statistics (a similar procedure is outlined in [15]).

The resulting values of $\alpha$ and $\alpha'$ are averaged in intervals of $\tau$. In Figs. and the
data are shown for two different types of absorption models. The observed slope $\alpha$ (lower set of points in green) displays a power-law index of approximately $-2.4$ at small optical depth (in the first bin). Up to an optical depth of $\tau \approx 1$, the observed slope softens to an average value of $\alpha \approx -3.5$, consistent with intrinsic $\alpha' \approx -2.4$. However, with further increasing optical depth, the observed slope $\alpha$ increases again until for $\tau \gtrsim 2$, $\alpha \approx -2.4$. The result is very similar for both models and repeats also for other tested models of gamma-ray absorption.

4. Discussion

The observations discussed above as well as the update on searches for anomalous transparency presented here indicate a puzzling feature in the observed gamma-ray spectra: at optical depth $\tau \gtrsim 2$ the spectra have a similar spectral slope as at small optical depth, consistent with previous analysis which have considered the global (i.e., over the entire observable energy range covered for each source) power-law index $\alpha'$.\footnote{\cite{10,12}}

4.1. Modification of Gamma-Ray Propagation in the Presence of Light Pseudoscalars: ALPs

In the presence of transversal magnetic fields, gamma-rays can mix with a light (mass in the range of $\mu$eV-neV) pseudoscalar fundamental bosons leading to an attenuation of the energy spectrum above a critical energy which depends on the mass of these particles (so-called ALPS- axion-like particles; for a review see \cite{18}) as well as on the magnetic field.\footnote{\cite{19}} While the photonic part of the propagating beam is attenuated in the EBL, the pseudoscalar fraction can in principle propagate largely unimpeded until reconverting, e.g., in the Galactic magnetic field (see Fig. 2 note, the mixing in the inter-galactic space was assumed to be negligible). The mixing can at most convert 1/3 of an unpolarized photon beam into an ALPs beam, of which at most 2/3 can reconvert into photon fields. Overall, in the most favorable conditions, a fraction of $1/3 \cdot 2/3 = 2/9$ of the initial photon beam can re-appear through the effect of conversion and re-conversion. This component will be however dominating over the attenuated beam if the optical depth $\tau \gtrsim \ln(2) \approx 0.7$ (assuming no mixing in inter-galactic space, the photon beam suffers absorption and is depleted to $2/3 \exp(-\tau)$; when entering the re-conversion region in the halo magnetic field of the Milky Way, in maximum mixing, 1/3 of the photons will convert to ALPs, leaving $4/9 \exp(-\tau) + 2/9$, where the last term is the re-converted ALPs part of the beam; in total $4/9(\exp(-\tau)+1/2)$ can be observed and once $\tau > 2$, the reconverted part of the beam will dominate). This is in qualitative agreement with the observation of a hardening of the observed spectrum for the part of the spectra observed at an optical depth $\gtrsim 1$ as discussed above. Note, a more quantitative study has been carried out indicating...
that the required mixing to explain the observations has to be close to maximum, still consistent with other constraints on possible photon-ALPs coupling.

4.2. **Modification of gamma-ray propagation in the presence of Lorentz invariance violation**

The effect of Lorentz invariance violation is expected to be of relevance at energies approaching the Planck scale. However, for the propagation of gamma-rays at TeV energies, the threshold for pair production is shifted leading to an energy dependent and characteristic deviation of the optical depth at energies above $\approx 10$ TeV. For some nearby objects like e.g., Mkn 501 ($z = 0.034$) or Mkn 421 ($z = 0.031$), the observed gamma-ray spectra are sensitive to this effect, observations with future instruments will have the potential to search for the spectral imprint with sources at larger distances. The analysis of gamma-ray spectra presented here indicates indeed a deviation from the expected absorption. However, the effect is not tied to a particular energy scale, but rather to a level of absorption ($\tau \gtrsim 1$). This is at first sight inconsistent with the expectation of a Lorentz-invariance violating effect. However, there are some proposals in which a more complicated structure of the vacuum would lead to a variation of the photon dispersion relation depending on the line of sight or distance of the object. In this case, such a model may offer an explanation for the observations.

4.3. **Ultra-high energy cosmic-rays and cascading**

Blazars and flat-spectrum radio quasars are attractive candidates for the sites of acceleration of ultra-high energy cosmic-rays (UHECRs), even though neither the
directions of UHECRs nor of energetic neutrinos have so far been found to correlate significantly with nearby blazars or active galactic nuclei in general. In a scenario, where blazars are powerful accelerators of UHECRs with a luminosity (in particle acceleration) of $\approx 10^{44}$ ergs/s, the observed gamma-ray emission may be of secondary origin. While the approach works well in individual cases, it requires fine-tuning to explain all the data: The transition of primary to secondary gamma-ray dominated part of the energy spectrum depends only on the ratio of primary gamma-ray luminosity and UHECR luminosity. Unless this ratio is tied to the distance in the right way, it would be difficult to reproduce the observed hardening of the spectrum.

5. Conclusions

The gamma-ray spectra of extra-galactic sources in the energy range from 100 GeV to tens of TeV continue to be of interest in the context of propagation in the extra-galactic medium. The standard picture of pair-production absorption in the extra-galactic background light seems to be incomplete. It does not explain the observations, especially in the tail of the energy spectra observed at optical depth $\tau \gtrsim 1$, where in the case of maximum mixing of photons with light axion-like particles, a recovery of the absorbed photon beam is expected to dominate. Alternative explanations (including effects of Lorentz-invariance violation as well as UHECR induced cascades) are attractive possibilities but require additional assumptions/fine-tuning. Clearly, the future gamma-ray instrumentations, both at the high energy end (e.g., TAIGA-HiSCORE, LHAASO) as well as at the low energy end (CTA) will provide important observations to clarify the observational situation.

Acknowledgements

The author is thankful for the organizers and the chairs of the session HE1 Experimental tests of fundamental physics with high energy gamma-rays (Alessandro de Angelis and Razmik Mirzoyan) for adding this topic to the very interesting session and to Marco Roncadelli for providing very useful comments on the manuscript. Without the last-minute help of R.P. Feller, it would not have been possible to finish this article in time, thank you for the support!

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