Abstract. Very high energy gamma-ray data obtained by CAT and HEGRA from active galactic nucleus Mkn 501 are used to constrain the cosmic Mid-Infrared background. While the entire infrared and submillimeter spectrum shape based on models has been fixed and the density scaled as a whole in previous studies, recent measures on the low and high energy infrared background are extensively used in this paper. In this original approach the infrared distribution is only varied in the unexplored 3.5-100 μm region. With conservative hypothesis on the intrinsic spectrum of Mkn 501, an upper limit of 4.7 nW.m⁻².sr⁻¹ between 5 and 15 μm is derived, which is very close to the lower limit inferred from deep ISOCAM cosmological surveys at 15 μm. This result is shown to be independent of the exact density of the λ < 3.5 μm and λ > 100 μm infrared distribution within the uncertainties of the measurements. Moreover, the study presented here rules out a complete extragalactic origin for the 60 micron tentative background detection as found by Finkbeiner et al. (2000).

Key words: Cosmology: diffuse radiation; Infrared: general; Gamma-rays: observations; BL Lacertae objects: Mkn 501
New constraints on the Cosmic Mid-Infrared Background using TeV gamma-ray astronomy

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1. Introduction

Our knowledge of the early epochs of galaxies has recently increased thanks to the observational evidences provided by UV/Vis/Near-IR, far-IR and submillimeter (submm) surveys of high-redshift objects. In a consistent picture, galaxy formation and evolution can also be constrained by the background radiation which is produced by the line-of-sight accumulation of all extragalactic sources.

In the last two years the Extragalactic Background (EB) at visible, IR and submm wavelengths has been finally constrained by both very deep source counts and upper limits on the diffuse isotropic emission at shorter wavelengths, and measurements in the submm range (see Gispert et al. 2000 for a review).

The Cosmic Infrared Background (CIB) detected in the COBE data at wavelength greater than 100 $\mu$m (Fixsen et al. 1998, Hauser et al. 1998, Schlegel et al. 1998, Lagache et al. 1999) contains a surprisingly large fraction of the background due to distant galaxies. The spectrum implies that the submm part of the CIB cannot be dominated by the emission of the galaxies which accounts for most of the CIB at 150 $\mu$m, and thus contains a unique information about high redshift IR galaxies. Considering the variety of long wavelength spectra observed for these galaxies, Gispert et al. (2000) have shown that a co-moving production rate of far-IR radiation with strong evolution at low redshifts but little evolution between redshifts 1 and 4 is the only solution allowed by the CIB.

The search for the UV, optical, near-IR and mid-IR EB (from 0.2 to 2.2 $\mu$m) obtained by summing up the contributions of galaxies using number counts currently gives only lower limits; but the flattening of the faint counts suggests that we are now close to convergence. Nevertheless, number counts give a good determination of the background only if the full flux of the sources is properly taken into account (Bernstein et al. 1999) and if diffuse components are negligible. In fact, studies of the diffuse COBE emission (Gorjian at al. 2000; Dwek & Arendt 1998; Cambrézy et al. 2000) suggest that a significant fraction of the EB is missed from number counts integrals in the near-IR.

Due to the bright zodiacal foreground emission (see for example Kellsall et al. 1998), EB determinations from 5 to about 80 $\mu$m are very difficult. In this wavelength range, EB constraints come mostly from deep IR cosmological surveys as the ones performed with ISOCAM (e.g. Elbaz et al. 1998). A more controversial tentative CIB detection at 60 $\mu$m has also been published using DIRBE data (Finkbeiner et al. 2000).

It has been suggested that observations of the TeV spectrum of extragalactic sources can be a powerful tool to constrain the CIB spectrum (Nikishov 1962; Gould & Schreder 1967; Stecker et al. 1992), especially around 10 $\mu$m, where the EB constraints are today very weak. As a matter of fact, TeV gamma rays propagating in the intergalactic medium undergo absorption through electron pair production on CIB photons. Using sources Mkn 421 and Mkn 501, meaningful upper limits have been established (see Malkan & Stecker 1998, Funk et al. 1998, Macinn & Primack 1996, Stanev & Franceschini 1998, Guy et al. 2000 for example).

In this paper, gamma-ray data are used, together with the best presently available direct CIB measurements (rather than CIB models), to improve the constraints in the most difficult spectral region, near the maximum of the zodiacal emission. The paper is organised as follows. We discuss in Sect. 2 the CIB measurements that are going to be used. Sect. 3 presents the TeV gamma-ray data. The determination of the upper limit is explained and done in Sect. 4 and 5. In Sect. 6, we compare our upper limit with lower limits derived from deep source counts obtained with the ISOCAM instrument aboard ISO (Elbaz et al. 1998, Metcalfe et al. 2000) and discuss the CIB distribution shape from 10 to 100 $\mu$m. Cosmological impli-
cations are then discussed. Finally, in section 7, the consequences on the physical parameters of Mkn501 regarding the internal absorption are briefly considered.

2. CIB density distribution

This study aims at deriving upper limits on the minimum of the CIB distribution lying in the Mid-IR (5-80 µm) region. In the Far-IR region, the distribution is constrained to account for the 100 µm determination from Lagache et al. (1999), which is in very good agreement with the value of Finkbeiner et al. (2000); data at longer wavelengths are not relevant for this study as they are beyond the threshold of the hardest TeV photons. In the Near-IR region, three different hypothesis, parametrised in this work by polynomial fits between 0.2 and 3.5 µm, are considered: the first one (dashed-dotted line in Fig. 1, referred as HDF + spectro) is derived from HDF results combined with ground-based spectrometry (Bernstein et al. 1999) and the third one (dotted line in Fig. 1, referred as Cambresy) is based on (Cambresy et al. 2000) points at 1.25 and 2.2 µm linked to the UV point at 0.2 µm (Bowyer et al. 1991 combined with Armand et al. (1994)), as it is clearly incompatible with HDF and HDF + spectro hypothesis1. All these parametrisations are required to agree with the 3.5 µm measurement from Gorjian et al. (2000); HDF and HDF + spectro hypothesis also include the 1.25 and 2.2 µm points from Wright (2000).

The CIB coming from the line of sight accumulation of all extragalactic sources is expected to have a smooth spectrum. The CIB might present a minimum between the stellar dominated part and the interstellar dust dominated one between 3 and 15 µm. To make optimum use of the upper limits that TeV gamma rays can provide we thus use an empirical model for the CIB with a small number of free parameters (λ_{min}, f_{min}) which interpolates between 3.5 and 100 µm two segments of parabola (in log-log plot) linking the 3.5 or 100 µm points to the minimum located at (λ_{min}, f_{min}) with a null first derivative at this point. The CIB empirical density distribution is shown in Fig. 1 for λ_{min} = 10 µm and f_{min} = 2, 4 or 6 nW m^{-2} sr^{-1}.

3. TeV gamma-ray astronomy data

The TeV source Mkn 501 is the second closest X-ray selected BL Lac object after Mkn 421 with a redshift z ~ 0.034. During the 1997 outburst which lasted several months, Mkn 501 was observed intensively in X-rays (BeppoSAX: Pian et al. 1998, RXTE: Lamer & Wagner 1998) and TeV γ-rays (Whipple: Catanese et al. 1999; CAT: Djannati-Ataï et al. 1999). The exceptional April 16, 1997 flare was observed by BeppoSAX and low-energy threshold (~ 300 GeV) Whipple and CAT atmospheric Cherenkov telescopes, allowing the derivation of the energy spectrum with good accuracy in a broad dynamical range.


In this paper, CAT and HEGRA data from 400 GeV to 17 TeV are used. Due to bad weather, the HEGRA telescope system could not observe this flare. But the HEGRA observations of Mkn 501 revealed that, despite flux variations in sub-day time-scales, the shape of the energy spectrum above 1 TeV remained essentially stable throughout the entire state of high activity in 1997.

Fig. 1. Assumed shapes of the CIB density distribution between 0.2 and 100 µm. Each profile between 3.5 and 100 µm is characterised by the position of the minimum (λ_{min}, f_{min}). In this example λ_{min} = 10 µm. See the text for details. Arrows show the 90 % interacting interval of target radiations for a 4 or 17 TeV photon (for f_{min} = 4 nW m^{-2} sr^{-1}). The full line links together the (HDF+spectro) points (0.3 to 0.8 µm), the (Wright 2000) points (1.25 to 2.2 µm) and the (Gorjian et al. 2000) points (2.2 to 3.5 µm). The dashed-dotted line links together smoothly the HDF points to the (Wright 2000) and (Gorjian et al. 2000) points. The dotted line links together the UV measurement at 0.2 µm, the (Cambresy et al. 2000) points (1.25 to 2.2 µm) and the 3.5 µm (Gorjian et al. 2000) points.

1 However, we will see (Sect. 5.2) that the impact of the density below 1 µm is ≈null
The HEGRA ‘time-averaged’ spectrum (Aharonian et al. 1999b) can therefore be used after normalisation to the CAT April 16, 1997 spectrum at $E = 1 \text{ TeV}$ with the rescaling factor of $\approx 2.2$ (Guy et al. 2000). At these energies the agreement between the CAT and HEGRA spectra is quite impressive. Below 1 TeV, CAT points are used solely since in this energy region both the statistical and systematic errors of the data obtained close to the energy threshold of the HEGRA telescope system are significantly larger than CAT data uncertainties.

4. Unfolding TeV spectra

The influence of low energy photons in the Universe on the propagation of Very High Energy (VHE) gamma-rays was pointed out by Nikishov (1962). An original way of using ground-based TeV observations of distant sources to probe the CIB was given by Stecker et al. (1992). The propagation of Very High Energy (VHE) gamma-rays using ground-based TeV observations of distant sources was pointed out by Nikishov (1962). An original way of the CIB energy distribution is assumed to be

$$\lambda_{\text{CIB}} \approx \frac{E}{2mc^2} \lambda_C$$

where $\lambda_C = h/(mc)$ is the Compton wavelength of the electron. As shown in Fig. 1, $\gamma$-photons with energy between a few TeV and 20 TeV “see” CIB photons with wavelengths between 3.5 and 100 $\mu$m.

In such an interaction between a gamma-ray of $(1 + z)E$ and an infrared photon of energy $(1 + z)\epsilon$, where $z$ is the redshift, $E$ and $\epsilon$ the observed energies at $z = 0$, the pair production threshold is $E\epsilon (1 + z)^2 (1 - \cos \theta) > 2 (mc^2)^2$ where $\theta$ is the angle between photons and $m$ the rest mass of the electron. The cross-section can be written as (Heitler 1960):

$$\sigma = k (1 - \beta^2) \left( \frac{2\beta (\beta^2 - 2) + (3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) }{1 - \beta^2} \right) \text{ cm}^2$$

with $\beta = \left( 1 - 2 (mc^2)^2 / (E\epsilon (1 - \cos \theta)) (1 + z)^2 \right)^{1/2}$ and $k = 1.25 \times 10^{-25}$. If the infrared photons have a density number $n(\epsilon) \text{ dc m}^{-3}$, the corresponding optical depth for attenuation is

$$\tau(E) = \int_0^{\frac{2}{3}} f_0 \int_1^{z/z_s} dz (1 + z)^{1/2} \int_{1-}^{E} d\epsilon (cos \theta) \frac{1-\cos \theta}{2} \int_{\epsilon_s}^{\epsilon} \epsilon d\epsilon n(\epsilon) \sigma(E, \epsilon, \theta)$$

where $\epsilon_s = 2(mc^2)^2 / (E(1 - \cos \theta)(1 + z)^2)$, $z_s$ is the redshift of the source, $c$ the light speed, and $H_0$ the Hubble parameter (assumed here equal to 65 km s$^{-1}$ Mpc$^{-1}$). For this equation, the density parameter $\Omega_0$ was chosen close to unity. The detected flux is then attenuated by a factor $e^{-\tau(E)}$. The CIB energy distribution is assumed to be independent of $z$ as the $\gamma$-ray source redshift is very low (0.034).

The maximum cross-section is reached for an infrared photon wavelength of $\lambda_{CIB} \approx \lambda_c \frac{E}{2mc^2}$ where $\lambda_c = h/(mc)$ is the Compton wavelength of the electron. As shown in Fig. 1, $\gamma$-photons with energy between a few TeV and 20 TeV “see” CIB photons with wavelengths between 3.5 and 100 $\mu$m.

![Fig. 2. Shapes of the reconstructed TeV spectra. The open circles show the observed CAT+HEGRA TeV spectrum while the filled symbols show the absorption corrected spectra (HDF + spectro hypothesis). The results of the parabola fit are superimposed.](image)

5. Upper limit on the CIB

5.1. Method

To turn out the absorption corrected spectra into an upper limit on the CIB density, the intrinsic spectral energy density of Mkn 501 is assumed to be convex in the multi-TeV region (Guy et al. 2000). This conservative hypothesis is based on the fact that no natural physical process can re-inject energy above the Inverse-Compton bump maximum. Both Klein-Nishina effect and auto-absorption within the source would cause the flux to decrease more and more rapidly as a function of energy. In the framework of more complex hadronic models this convex shape is also expected, either because of proton-initiated-cascade (often modelized as a broken power-law around 3 TeV), or due to the inclusion of $\mu$-synchrotron radiation (Mannheim, private communication). Even in the extreme case where proton synchrotron radiation is at the origin of the TeV bump (Aharonian 2000), the shape of the emission remains convex.

Looking at the absorption corrected spectra shown in Fig. 2, it cannot be excluded that the maximum of the so-called Inverse-Compton peak is not yet reached at 17 TeV when a large amount of CIB radiation ($f_{\text{min}} > 6 \text{ nW m}^{-2} \text{ sr}^{-1}$) is assumed. Physical parameters (essentially magnetic field and Doppler factor) required to produce such a spectral energy distribution maximum...
above 17 TeV are substantially disfavoured but, even in this case, the \( \nu F(\nu) \) shape should remain convex. This latter point is ensured by BeppoSAX 1-100 keV measurements (Pian et al. 1998) showing a clearly convex spectrum before the synchrotron bump maximum (around 100 keV) which is supposed to be mimicked by the TeV-spectrum before the so-called Inverse-Compton bump maximum. This hypothesis is reinforced by the fact that the sub-TeV slope, which is independent of the CIB density beyond 3.5 \( \mu \)m, effectively reflects the X-ray slope in the keV range. This behaviour (together with the correlated variability reported e.g. by Aharonian et al. (1999a) and Djannati-Ataï et al. (1999)) indicates that the same population of particles is at the origin of both X-ray and \( \gamma \)-ray emissions, whatever this population is. In particular, the self-synchro-Compton model fits satisfactorily the absorption corrected data (Guy et al. 2000).

In order to quantify the concavity of the absorption corrected spectrum, a parabola fit is performed from 3.3 to 17 TeV in the plane \((\log(\nu), \log(\nu F(\nu)))\). This function, which is simple, is chosen for its constant second derivative \( a = \frac{d^2(\log(\nu F(\nu))}{d(\log(\nu))} \), avoids the choice of a particular test-energy and fits satisfactorily the data. The previous physical constraint on the concavity of the TeV spectrum simply reads as \( a < 0 \). The parameter \( a \) is computed for \( f_{\min} \) in the range 0.1-7 nW m\(^{-2}\) s\(^{-1}\). Fig. 2 shows the result of the parabolic fit in several cases, superimposed to the absorption corrected experimental points. The fit under-estimates the energy density of the hardest photons, ensuring that the local second derivative is under-estimated and thus making the test conservative.

Furthermore, when \( a > 0 \), fitted parabola with \(-b/2a > 17 \) TeV, where \( b = \frac{d(\log(\nu F(\nu))}{d(\log(\nu))} \), are accepted. This ensures that, whatever the concavity, no fitted function decreasing with \( \nu \) over the energy range considered here will be excluded. Asking for a decreasing \( \nu F(\nu) \) distribution is the most natural constraint in the previously mentioned (Inverse-Compton bump maximum below or around 1.4 TeV) most favoured case. This double test on both the first and the second derivative makes the resulting upper limit very conservative.

5.2. Reliability of the upper limit

Fig. 3 shows the impact of the main uncertainties on the measured part of the CIB density distribution on the absorption corrected TeV spectrum. The observed spectrum of Mkn 501, combining CAT and HEGRA data, is plotted with open circles in panel a). Spectra corrected from CIB absorption are superimposed with filled symbols in different cases: a) \( HDF, HDF + spectro \) and \( Cambresy \) hypothesis b) 3.5 \( \mu \)m \( \pm 1 \) \( \sigma \) (NIR); c) position of the minimum \( \lambda_{\min} = 5 \) or 15 \( \mu \)m; d) 100 \( \mu \)m value \( \pm 1 \) \( \sigma \) (FIR). By default, \( \lambda_{\min} = 10 \) \( \mu \)m.

From panel a), it can be seen that the impact of the NIR density below 1 \( \mu \)m is null beyond a few TeV, as the threshold for pair production for a 1 TeV photon is approximately 1 \( \mu \)m. Furthermore, even below 1 TeV, \( HDF \) and \( HDF + spectro \) hypothesis lead to the same absorption corrected spectrum. Therefore, only the \( HDF + spectro \) and \( Cambresy \) hypothesis will be considered hereafter. The value of \( \lambda_{\min} \) (panel c) and the FIR density at 100 \( \mu \)m - in a minor way - (panel d) can slightly change the very high energy tail of the source spectrum (above 10 TeV) while uncertainties on the 3.5 \( \mu \)m measurement have no sizeable impact (panel b). So, the uncertainty on the 100 \( \mu \)m measurement and a range of values for the parameter \( \lambda_{\min} \) (5-15 \( \mu \)m) must be taken into account when deriving upper limits on the MIR density.

The evolution of the parameter \( a \) in function of \( f_{\min} \) is presented in Fig. 4 in the case \( \lambda_{\min} = 10 \) \( \mu \)m and a \( HDF + spectro \) CIB density distribution while the values of \( f_{\min} \) corresponding to a null parameter \( a \) (within 5\( \sigma \)) for several values of \( \lambda_{\min} \) are gathered in Tab. 1 for all hypotheses regarding the NIR or the FIR density.
5.3. Conclusion

The results of this work are given in Tab. 1. The 3.5-100 μm photons being essentially absorbed by 2-15 TeV gamma-rays, the CAT and HEGRA spectra of Mkn 501 are particularly well suited to test the MIR density. The high flux allows a good spectral resolution and the simultaneous X-ray data provides crucial information on the synchrotron bump shape. The MIR upper limit derived in this paper is robust as it is almost independant of the NIR hypothesis (within 1 σ error), and only marginally depends on the FIR flux hypothesis (within 1 σ error). Somewhat more surprising is that the exact position of the minimum in the 5-15 μm range significantly affects the upper limit (as seen in Fig. 3). The quite high sensitivity to the value of λmin is due to the fact that the shape of the γ-ray spectrum strongly depends on the CIB density distribution between 5 and 50 μm (and not only on its mean intensity). In other words, more absorption is allowed if the mid-IR spectral distribution, and thus the energy dependence of the extinction, gives an acceptable shape of the TeV spectrum of the source.

This limit is conservative, both due to the method which tends to under-estimate the high energy flux density and to the weak hypothesis regarding the spectrum concavity. Indeed, internal effects, such as Klein-Nishina cut-off and self-absorption, lead to very sharp multi-TeV intrinsic spectra. The upper limit is more constraining than the indirect upper limit derived from the same data on Mkn 501, which relies on a global CIB scaling (Guy et al. 2000). Moreover, whatever the position of the minimum in the range 5-15 μm, the Mid-IR density upper limit remains lower than 4.7 nW m⁻² sr⁻¹.

Our results are in agreement with previous works: for example, Stanev & Franceschini (1998) obtained an upper limit of 4 to 5 nW m⁻² sr⁻¹ at 15 μm with two CIB hypotheses and Stecker & De Jager (1997) derived an upper limit of 4 nW m⁻² sr⁻¹ at 20 μm. It shows the “robustness” of the method based on TeV gamma-rays absorption by IR photons, essentially due to the peak in the pair production cross section. The NIR and FIR fluxes are now confirmed by direct measurements and these observational results enhance the reliability of the constraints on the MIR intensity distribution.

An approach similar to ours has also been proposed by Dwek et al. (2000) who found a CIB density lower than 5 nW m⁻² sr⁻¹ in the range 6-30 μm and lower than 10 nW m⁻² sr⁻¹ at 60 μm.

6. Discussion on the CIB measurements

6.1. The case of the 60 micron tentative EB detection

From analysis of the DIRBE weekly averaged sky maps, Finkbeiner et al. (2000) have detected substantial flux in the 60 μm DIRBE channel in excess of expected zodiacal and Galactic emission. The observed signal is consistent with an isotropic background at the level νIν = 28.1 ± 1.8 ± 7(syst) nW m⁻² sr⁻¹. While this new excess is not necessarily the CIB, they have ruled out all known sources of emission in the solar system and Galaxy. They therefore tentatively interpret this signal as the CIB. However, they point out that the IR excess exceeds limits on the EB derived from the inferred opacity of the inter-galactic medium to observed TeV photons.

In the assumption that the residual observed at 60 μm is the CIB, we can compute, using the same method as previously, a Mid-IR upper limit on the CIB. With λmin=10 μm, we obtain an upper limit of 1.0 nW m⁻² sr⁻¹ which is clearly incompatible with the lower limit of 3.3 nW m⁻² sr⁻¹ at 15 μm, derived from deep ISOCAM surveys (Biviano et al. 2000). Even when the 60 μm tentative measurement is decreased by 1 σ, the absorption corrected TeV spectrum in unacceptable (upper limit of 1.3 nW m⁻² sr⁻¹). With λmin=15 μm, the upper limit becomes marginally compatible with the ISO-CAM result (upper limit of 2.2 nW m⁻² sr⁻¹). Thus, as pointed out by Finkbeiner et al. (2000), we conclude that the 60 μm excess is certainly not only CIB. It contains residual foreground emission, more likely zodiacal residual emission (see Sect. 6.3).
6.2. The EB around 15 µm

Fig. 5 shows together our results with the 6.5 and 15 µm lower limits obtained by integrating the energy from sources observed in ISOCAM deep fields. The flattening of the faint counts at 15 µm (Metcalfe et al. 2000) suggests that we are now close to convergence and thus that number counts are not very far from the true value of the EB (if no diffuse emission contributes to it). Number counts give 3.3 ±1.3 nW m⁻² sr⁻¹ (Biviano et al. 2000).

Using the model of galaxy evolution from Dole et al. (in prep), we find an EB of about 4.4 nW m⁻² sr⁻¹, which is very close to the upper limit derived using the gamma-rays for a high value of λₘᵞᵣ. This tends to show that the absorption in the gamma-ray spectrum of Mkn 501 is mainly, or entirely due to absorption through electron pair production on CIB photons (see Sect. 7). Thus, the upper limit obtained with λₘᵞᵣ=15 µm is probably a best guest of the CIB level. Using a different argument based on the expected intrinsic shape of the TeV spectrum and the “high” CIB model from Stecker & De Jager (1998), Konopelko et al. (1999) also concluded that the observed curvature of the spectrum of Mkn 501 could be naturally explained by the extragalactic absorption.

6.3. CIB shape between 10 and 100 µm

In the previous sections, the CIB density distribution was assumed to be described by a parabola between the minimum and the 100 µm Lagache et al. (1999) point. This function may underestimate of the EB light and it is important to study the consequences of a change in the CIB shape. As illustrated in Fig. 6, two more realistic (and less conservative) distributions have been tested with a minimum at (10 µm, 2.8 nW m⁻² sr⁻¹), i.e. in agreement with ISO-CAM measurements. In each case, even taking into account only the 140 µm Lagache et al. point, the shape of the absorption corrected TeV spectrum is rejected by the physical criteria given in section 5.2. This means that, at least, the 100 µm Lagache et al. (1999) measurement may be overestimated.

The DIRBE zodiacal emission model was obtained by Kelsall et al. (1998) relying on its time variability². This model is critical to get the CIB in the near infrared. Its accuracy can be estimated using the residuals observed at wavelengths were the zodiacal emission is maximum (12 and 25 µm). The residual emission, obtained by Hauser et al. (1998), has in fact a spectrum very similar to the zodiacal one. The residuals are about 470 nW m⁻² sr⁻¹ at 12 and 25 µm. The work presented just before reveals that this best model may underestimate the zodiacal emission as the uncertainties on other contributions (instrumental and interstellar) are significantly smaller. We can thus make a conservative estimate of the amount of zodiacal emission which is not removed by this model at 12 and 25 µm to be about 400 nW m⁻² sr⁻¹. The amount not removed at 60 and 100 µm is thus 40 nW m⁻² sr⁻¹ and 8.4 nW m⁻² sr⁻¹ (using the Kelsall et al. 1998 smooth high latitude zodiacal cloud colour ratios). This reduces the CIB at 100 µm from 23.4 to 15 nW m⁻² sr⁻¹. At 60 µm the extra-zodiacal emission to be removed (40 nW m⁻² sr⁻¹) is comparable to the residuals and thus no meaningful value can be obtained on the CIB at this wavelength. Using the same arguments, the extra-zodiacal emission to be removed at 1.25 µm in the Cambésy et al. (2000) work is 38.0 nW m⁻² sr⁻¹ from the published result of 56.9 nW m⁻² sr⁻¹.

The impact of a larger zodiacal emission on the upper limits in the MIR range is shown in Fig. 7. With a flatter CIB distribution, the upper limit at 10 µm increases from 2.8 to 3.7 nW m⁻² sr⁻¹. It remains very close to the direct measurement from ISOCAM at 15 µm.

In addition to a high interest for cosmology and galaxy evolution, a better knowledge of the entire CIB shape

² Other more empirical models have also been built by Wright (2000) and Finkbeiner et al. (2000).
7. Discussion on Mkn501 physical parameters

In the previous section, so as to derive a conservative upper limit on the CIB density, no internal absorption within the source has been taken into account. Nevertheless, the ISOCAM 15 µm point (at 3.3 nW m⁻² sr⁻¹) gives a lower limit on the CIB density and, assuming this value to be a measurement, the resulting maximum possible absorption within the source can be estimated. The previous physical constraints on the absorption corrected spectrum can be applied again, assuming the minimum possible CIB density (to remain conservative), and varying the optical depth \( \tau_{AGN} \) due to \( \gamma - \gamma \) pair production within the jet of Mkn501.

To compute \( \tau_{AGN} \) in the TeV range, the low-energy spectrum (i.e. the energy distribution of target photons) has to be known. We use the approximation derived by (Bednarek & Protheroe, 1999) using a fit to the BeppoSAX observations made during the April 15/16 flaring activity together with an indication from OSSE observation made during the high state in 1997 April that the spectrum continued to approximately 500 keV with the same energy flux per log energy interval. Performing a numerical integration of the optical depth formula (cf Sect. 4), the authors show that, in the framework of homogeneous SSC model:

\[
\tau_{AGN} \approx 3 \times 10^{8} D^{-4.8} E^{0.4} t_{\text{var}}^{-1}
\]

where \( D \) is the Doppler factor of the blob where relativistic electrons are assumed to be confined, \( t_{\text{var}} \) is the variability time-scale of the source in seconds and \( E \) is the \( \gamma \)-rays energy in TeV. The efficiency usually associated with this mechanism has been supposed, as usual, equal to unity.

Both absorptions are compared in Fig 8. They look rather similar as the dominant behaviour is in \( E^{-2} \) in energy density. But the internal absorption is continuously increasing with energy while the CIB absorption exhibits a “plateau” around 1-4 TeV. Adding this new optical depth to the one associated with \( \gamma - \text{CIB} \) interactions, we derive a 5\( \sigma \) upper limit for \( 3 \times 10^{8} D^{-4.8} t_{\text{var}}^{-1} \) of 0.6 (computed with \( \lambda_{\text{min}}=15 \) µm and \( f_{\text{min}}=3.3 \) nW m⁻² sr⁻¹, i.e. for the ISOCAM point). With a reasonable variability time-scale around 1 hour, the resulting minimum Doppler factor is \( D > 11.7 \). Despite the large CIB absorption and the resulting stringent upper limit on the internal optical depth, these Doppler factors are in agreement with classical AGN descriptions and the simple homogeneous SSC model works satisfactorily. Nevertheless, it should be pointed out that this lower limit on the Doppler factor increases as the wavelength of the minimum of CIB density decreases and becomes infinite below \( \approx 10 \) µm when there is no space left for internal absorption, unless an inhomogeneous jet is assumed.

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Fig. 6. Consequences of a change in the CIB shape beyond 10 µm: hypothesis on the CIB density distribution (panel a) and corresponding absorption corrected high energy Mkn 501 spectra (panel b). Ordered by increasing densities, we consider the normal (i.e. parabolic) distribution (dots) and two cubic distribution linking the 10 µm minimum to the 140 µm Lagache et al point (squares) and the 100 µm Lagache et al point (up-triangles). Would be of great interest to unfold TeV spectra of extragalactic sources.

Fig. 7. CIB density vs wavelength: data and upper limits from VHE observation (\( \lambda_{\text{min}}=10 \) µm case). The HDF + spectra spectrum is linked to different points at 100 µm: Lagache et al. (1999) flux (23.4 nW m⁻² sr⁻¹, full line), the same Lagache et al. flux with a higher zodiacal background subtracted (15 nW m⁻² sr⁻¹, dashed line) and this point -1 \( \sigma \) (8.7 nW m⁻² sr⁻¹, dotted line). The number counts result from ISOCAM 15 µm (Biviano et al. 2000) is shown by the star.
Fig. 8. Optical depth of the TeV flux in function of the energy $E$. The stars symbolise the absorption due to the EB photons while the line shows the absorption due to IR photons in the inner jet ($\lambda_{\text{min}}=15 \mu\text{m}$, $f_{\text{min}}=3.3 \text{nW m}^{-2} \text{sr}^{-1}$).

With the next generation of instruments (VERITAS and MAGIC in the northern hemisphere, HESS and CANGAROO in the southern one) which will start operating in 2002/2003, good quality spectra of several AGNs at different redshifts, will be available. It will lead to, simultaneously, a better understanding of the TeV emission mechanism and a better knowledge of the CIB density distribution.

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8. Note added in proof

In this paper an early version of the Cambrésy et al. 2000 paper was used: the 1.25 $\mu$m flux was overestimated by 5%; it does not affect our results.