TeV Blazars and Cosmic Infrared Background Radiation

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Abstract. The recent developments in studies of TeV radiation from blazars are highlighted and the implications of these results for derivation of cosmologically important information about the cosmic infrared background radiation are discussed.

1 Introduction

Since early 90’s many papers have been published with an unusual combination of two keywords - Blazars and Cosmic-Infrared-Background (CIB) radiation. Formally, one may argue that there is no apparent link between these two topics.

- The blazars constitute a sub-class of AGN dominated by highly variable (several hours or less) components of broadband (from radio to gamma-rays) non-thermal emission produced in relativistic jets pointing close to the line of sight.
- CIB is a part of the overall diffuse extragalactic background radiation (DEBRA) dominated by thermal emission components produced by stars and dust, and accumulated over the entire history of the Universe.

While the blazars may serve as ideal laboratories for study of MHD structures and particle acceleration processes in relativistic jets, CIB carries crucial cosmological information about the formation epochs and history of evolution of galaxies. To a large extent, these two topics are relevant to quite independent areas of modern astrophysics and cosmology. Yet, the current studies of CIB and blazars, more specifically the sub-population of blazars emitting TeV gamma-rays (TeV blazars), are tightly coupled through the intergalactic (IG) absorption of TeV radiation by infrared photons of DEBRA.

The astrophysical/cosmological importance of this interesting effect (Nikishov, 1962; Gould and Schreder, 1966; Jelly, 1966; Stecker et al., 1992) was clearly recognized after the discovery of TeV $\gamma$-rays from two BL Lac objects – Mkn 421 and Mkn 501 (for review see e.g. Vassiliev 2000).

2 Cosmic Infrared Background Radiation

CIB basically consists of two emission components produced by stars and partly absorbed/re-emitted by dust during the entire history of evolution of galaxies. Consequently, two distinct bumps in the spectral energy distribution (SED) of red-shifted radiation at near infrared (NIR) $\lambda \sim 1-2 \mu m$ and far infrared (FIR) $\lambda \sim 100-200 \mu m$ wavelengths, and a mid infrared (MIR) “valley” between these bumps are expected. Because of the heavy contamination caused by foregrounds of different origin, predominantly by the zodiacal (interplanetary dust) light, the measurements of CIB contain large uncertainties. Moreover, these results only conditionally can be treated as direct measurements, because their interpretation primarily depends on the modeling and removal of these foregrounds. Therefore, the direct observations of CIB generally allow derivation of the flux upper limits rather than detection of positive residual signals. In Fig. 1 we show the CIB fluxes based on the latest reports, and refer the reader to the review article by Hauser and Dwek (2001) on the current status of direct observations of CIB.

Presently, the most reliable results are obtained from the COBE observations at NIR and FIR domains where the contribution of the zodiacal light becomes comparable with the CIB flux. This concerns, first of all, the FIR wavelengths at 140 and 240 $\mu m$ (Hauser et al., 1998, Schlegel et al., 1998, Lagache et al., 1999), and perhaps also at 100 $\mu m$ (Lagache et al., 1999; Finkbeiner et al., 2000) where the results of 3 different groups are in a reasonable agreement with each other, but somewhat higher compared to the theoretical predictions. If the reference of these fluxes to the truly extragalactic background is correct, this would imply that most of the star formation in the early Universe must occur in highly obscured, dusty environments.

Detections of CIB are claimed also at NIR - at 2.2 $\mu m$ and 3.5 $\mu m$ wavelengths (Dwek and Arendt, 1998; Gorjian et al., 2000; Wright and Johnson, 2001). These fluxes together with the J-band upper limit at 1.25 $\mu m$ (Wright and Johnson, 2001) and the fluxes of the optical light derived from the
HST data below 0.8 μm (Bernstein, 1998), agree with the recent theoretical calculations by Primack et al. (2001). An independent analysis of the COBE data by Cambresy et al. (2001), as well as the results of the Japanese IRTS satellite (Matsumoto et al. 2001) are in agreement with the fluxes at 2.2 μm and 3.5 μm reported by Wright and Johnson (2001), but at shorter wavelengths the claimed fluxes are noticeably higher compared to other measurements (see Fig. 1).

The “best guess” estimate of the SED at optical/NIR wavelengths of about 20-50 nW/m²sr is comparable with the FIR flux of about 40-50 nW/m²sr (Madau and Pozzetti, 2000). This indicates that an essential part of the energy radiated by stars is absorbed and re-emitted by cold dust. Our current knowledge of MIR, which carries information about the warm dust component, is quite limited. The only flux estimates in this band derived from the ISOCAM source counts at 6 and 15 μm (Franceschini et al., 2001) apparently should be taken as lower limits.

These measurements stimulated new calculations of CIB based on different phenomenological and theoretical (backward, forward, cosmic chemical evolution, semi-analytical, etc.) approaches. In spite of certain achievements, the ability of current (most successful) models to reproduce the CIB measurements nevertheless should not be overstated, because all these models contain a number of adjustable parameters and in fact are “primarily designed for that purpose” (Hauser and Dwek, 2001).

In Fig. 1 three CIB models are shown which provisionally may be assigned as “nominal” (1), “low” (2), and “extreme” (3) descriptions of CIB. The curve 2 corresponds to the so-called “LCDM-Salpeter” model of Primack et al. (1999), but assuming twice larger contribution of the dust component. Similar NIR spectra with a flux of about 10 nW/m²sr at 1 μm have been assumed by De Jager and Stecker (2001) and Franceschini et al. (2001). The curve 1 is close to the prediction by Primack et al. (2001) based on the so-called “Kennicutt” stellar initial mass function (IMF). And finally, the curve 3 is “designed” to match the extreme fluxes reported by Matsumoto (2000) and Cambresy et al. (2001) at NIR and Finkbeiner et al. (2000) at FIR.

### 3 Absorption of TeV gamma-rays in CIB

To calculate the mean free path of γ-rays \( \Lambda(E) \) in the IGM one must convolve the CIB photon number distribution \( n(\epsilon) \) with the pair production cross-section. Because of the narrowness of the latter, for broad-band photon spectra over half the interactions of a γ-ray photon of energy \( E \) occur with a quite narrow interval of target photons \( \Delta \lambda \sim (1 \pm 1/2)\lambda^* \) centered on \( \lambda^* \approx 1.5(E/1\,\text{TeV})\,\mu\text{m} \). This gives a convenient approximation for the optical depth \( \tau(E) = d/\Lambda(E) \)

\[
\tau(E) \approx 1 \left( \frac{u_{\text{CIB}}(\lambda^*)}{10\,\text{nW/m}^2\text{sr}} \right) \left( \frac{E}{1\,\text{TeV}} \right) \left( \frac{z}{0.1} \right) H_{60}^{-1} \]

where \( u_{\text{CIB}} = \nu I(\nu) = \nu^2 n(\epsilon) \) is the SED of CIB, \( z \) is the source redshift, \( H_{60} \) is the Hubble constant normalized to 60 km/s Mpc. No deviation of the observed γ-ray spectrum from the intrinsic (source) spectrum, e.g. by a factor of \( \lesssim 2 \), would imply \( \tau(E) \leq \ln 2 \), and consequently provide an upper limit on the CIB flux at \( \lambda^*(E) \). For example, this condition for 1 TeV γ-rays from Mkn 421 or Mkn 501 \((z \approx 0.03)\) gives \( u_{\text{CIB}} \leq 20\,\text{nW/m}^2\text{sr} \) around 1-2 μm.
averaged spectrum of Mkn 501 (Aharonian et al., 1999a). The star corresponds to the recently re-estimated flux at $E \approx 21$ TeV (Aharonian et al., 2001a). The vertical line at 17 TeV indicates the edge of the spectrum measured with high statistical significance.

Since this estimate is quite close to the recent NIR measurements (see Fig. 1), we may conclude that already at 1 TeV we detect significantly absorbed $\gamma$-radiation from Mkn 421 and Mkn 501. This is demonstrated in Fig. 2 where we present accurate numerical calculations of the mean free path of $\gamma$-rays for three CIB reference models shown in Fig. 1. The horizontal lines indicate the distances to the reported TeV blazars (see below), as well as to 2 nearby prominent extragalactic objects – the radiogalaxy M 87 and the ultraluminous starburst galaxy Arp 220. The curve 2 calculated for the CIB lower limit (model 2 in Fig. 2), should be treated as an upper limit for the mean free path. This implies that we cannot ignore the IG-absorption of TeV $\gamma$-rays from sources located beyond 1 Mpc. On the other hand, this gives a unique chance to extract information about CIB by detecting absorption features in TeV spectra of extragalactic objects.

Very often such a possibility is reduced to the search for sharp cutoffs in the energy spectra of extragalactic TeV sources (see e.g. Stecker et al., 1992). However, in many cases this could be a misleading recommendation. Indeed, the cutoff in a $\gamma$-ray spectrum does not yet imply an evidence for the IG-absorption and vice versa, the lack of the cutoff cannot be interpreted as absence of IG-absorption. It is interesting to note that all CIB models with conventional spectral shape between 1 and 10 $\mu$m, predict almost constant (energy-independent) mean free path of $\gamma$-rays, and correspondingly insignificant spectral deformation at energies between 1 and several TeV (Primack et al., 2001). The explanation of this effect is straightforward. If the spectrum of background photons in a certain energy interval has a power-law dependence, $n(\epsilon) \propto \epsilon^{-\beta}$, the mean free path in the corresponding $\gamma$-ray energy interval $\Lambda(E) \propto E^{1-\beta}$. Within $1 \mu m < \lambda < 10 \mu m$ the CIB spectrum is approximately described by a power-law $n(\epsilon) \propto \epsilon^{-1}$ or $u_{CIB} \propto \lambda^{-1}$ (see Fig. 1), therefore in the interval between 1 and several TeV the $\gamma$-ray mean free path only slightly depends on energy (Fig. 2). In order to demonstrate the impact of the IG-absorption, in Fig. 3 we show the SED of Mkn 501 together with the absorption-corrected spectra reconstructed for 3 CIB models shown in Fig. 1.

### 4 Observations of TeV Blazars

Many nonthermal extragalactic objects representing different classes of AGN and located within 1 Gpc are potential TeV sources. First of all this concerns the BL Lac population of blazars of which two nearby representatives, Mkn 421 ($z = 0.031$) and Mkn 501 ($z = 0.034$) are firmly established as TeV $\gamma$-ray emitters. The current list of extragalactic TeV sources contains 4 more BL Lac objects with reported signals at 4 to 6 sigma level: 1ES 2344+51 [Whipple (Catanese et al., 1998)] at $z = 0.044$, PKS 2155-304 [Durham (Chadwick et al., 1999)] at $z = 0.116$, 1ES 1959+650 [Telescope Array (Nishiyama et al., 1999) and HEGRA (Götting et al., 2001)] at $z = 0.048$, and 1ES 1426+428 [VERITAS (Horan et al., 2001) and HEGRA (Götting et al., 2001)] at $z = 0.129$.

Since the discovery of TeV $\gamma$-radiation of Mkn 421 (Punch et al., 1992), this object has been subject of intensive studies through multiwavelength observations. The TeV flux of the source is variable with typical average value between 30% to 50% that of the Crab Nebula, but with strong and rapid, as short as 0.5 h, flares (Gaidos et al., 1996) which correlate with the source activity at other wavelengths. Until the spectacular high state of the source in 2001, the spectral studies were based mainly on the data taken during a quiescent or moderately high states. In particular, the spectrum measured by HEGRA during the 1998 “ASCA” campaign (Takahashi et al., 2000) is fitted by a steep power-law with photon index $\Gamma \simeq 3$ (Aharonian et al., 1999b). The exceptionally bright and long-lasting activity of Mkn 421 in 2001 allowed the VERITAS (Krennrich et al., 2001) and HEGRA groups (Horns et al., 2001) to derive the time-averaged gamma-ray spectrum of the source in the high state which up to ~ 15 TeV is described as $dN/dE = KE^{\Gamma} \exp(-E/E_0)$, i.e. by the same canonical “power-law with exponential cutoff” function found earlier for the high-state, time-averaged spectrum of Mkn 501 (Aharonian et al., 1999a). The spectra of these sources are not, however, identical. In Fig. 4 we show the energy spectra based on approximately 40,000 and 60,000 TeV $\gamma$-ray events detected by HEGRA during the exceptionally high states of Mkn 501 in 1997 and Mkn 421 in 2001, respectively. They are described by different $[\Gamma, E_0]$ combinations: $\Gamma = 1.92 \pm 0.03$ and $E_0 = 6.2 \pm 0.4$ TeV for Mkn 501 (Aharonian et al., 1999a) and $\Gamma = 2.23 \pm 0.04$ and $E_0 = 4.0 \pm 0.4$ TeV (Horns et al., 2001). The power-law part of the spectrum of Mkn 421 is steeper, and the exponential cutoff starts earlier. Since both sources are located at ap-
approximately same distances, the difference in the cutoff energies may be interpreted as an evidence against the hypothesis which attributes the cutoffs to the pure IG-absorption effect.

For the typical energy resolution of Cherenkov telescopes of about 20% or larger, one has to be careful with conclusions concerning the spectral shape at energies beyond \( \approx 3E_0 \). Obviously for determination of spectra with sharper (super-exponential) cutoffs, a significantly better energy resolution is required. Motivated by this, HEGRA collaboration recently re-analyzed the “1997 high-state” spectrum of Mkn 501 using an improved method for energy reconstruction with \( \approx 12\% \) resolution achievable for the stereoscopic mode of observation (Hofmann, 2000). The new analysis confirms the result of the previous study up to 17 TeV, but constrains stronger the flux at 21 TeV (Aharonian et al., 2001a). With this new point, the Mkn 501 spectrum at very high energies is better described by a super-exponential cutoff (compare curves (a) and (b) in Fig. 3).

Despite the huge overall photon statistics, the spectra of both sources above 10 TeV can be determined using data accumulated over long periods of observations. Obviously, the time-averaged spectra of variable sources obtained in such way can be considered as astrophysically meaningful provided that the spectral shape is essentially time-independent, i.e. does not correlate with the absolute flux. Remarkably, it turned out that during the high state in 1997 the shapes of daily spectra of Mkn 501 remained essentially stable despite dramatic flux variations (Aharonian et al., 1999a), although for some specific flares significant spectral variations cannot be excluded. For example, the CAT group (Djannati-Atai et al., 1999) found an evidence for a non-negligible hardness-intensity correlation for the 1997 April 7 and 16 flares.

The sensitivity of current ground-based detectors is not sufficient to study the spectral variability of TeV radiation of Mkn 421 and Mkn 501 in quiescent states on timescales less than several days. However, even the time-averaged spectra of these sources in low states are of certain interest. The HEGRA observations of Mkn 501 in 1998 and 1999, when the source was at a \( \approx 10 \) times lower flux level compared to the average flux in 1997, revealed a noticeable steepening of the energy spectrum (Aharonian et al., 2001b). This seems to be true also for Mkn 421, at least at low energies. While the spectrum of this source in a quiescent state has a steep power-law spectrum with photon index \( \Gamma \approx 3 \), the time averaged spectrum of the 2001 outburst is significantly flatter, with \( \Gamma \approx 2.2 \) around 1 TeV.

The SEDs of BL Lacs are expected to be very hard up to TeV energies, therefore the imaging atmospheric Cherenkov telescopes (IACTs) are nicely suited to search for short signals from these objects. In particular, the HEGRA, CAT and VERITAS IACTs can follow \( \approx 10^{-11} \) erg/cm\(^2\)s (at 1 TeV) flares of Mkn 421 and Mkn 501 on timescales less than several hours, and thus are well-matched to the sensitivity and spectral coverage of X-ray satellites like RXTE, BeppoSAX and XMM for multiwavelength monitoring of flux variations. This is a key condition which makes the simultaneous X- and \( \gamma \)-ray observations meaningful and very important (e.g. Pian et al., 1998, Sambruna et al., 2000; Maraschi et al., 1999; Kataoka et al., 1999; Krawczynski et al., 2000; Takahashi et al., 2000). The best so far results in this regard became available recently, after the well coordinated multiwavelength campaigns of spectacular flares of Mkn 421 in 2001. On several occasions, truly simultaneous observations by RXTE and TeV instruments with durations up to 6 hours per night were carried out. A nice sample of such events,
cesses in jets, it is crucial to search for sub-hour timescales (see Fig. 5). (Fossati et al., 2001) shows a clear keV/TeV correlation on the 2001 March 22 flare detected by RXTE and VERITAS on March 21/22, 2001 (Horns et al., 2001).

The studies of spectral evolution of TeV gamma-rays

5 Radiation mechanisms of TeV gamma-rays

the 2001 March 22 flare detected by RXTE and VERITAS (Fossati et al., 2001) shows a clear keV/TeV correlation on sub-hour timescales (see Fig. 5).

For deep understanding of acceleration and radiation processes in jets, it is crucial to search for spectral variability on timescales comparable to the characteristic dynamical times of about 1 h. The HEGRA IACT system is able to perform such studies, if the flux at 1 TeV exceeds 1-2 Crab units, $J_{\text{Crab}}(E \geq 1 \text{ TeV}) \simeq 1.7 \times 10^{-11} \text{ ph/cm}^2\text{s}$. The strongest flares of Mkn 421 in 2001 provide us with such unique data. The preliminary spectral analysis of observations of these flares (Horns et al., 2001) shows a complex picture. If the spectra of some of these flares do not show noticeable spectral changes, the others, in particular the 21/22 March 2001 flare demonstrates an impressive correlation of the hardness ratio with the absolute flux (see Fig. 6).

![Fig. 6. Time-evolution of the absolute flux and the hardness ratio of TeV radiation of Mkn 421 observed by the HEGRA IACT system on March 21/22, 2001 (Horns et al., 2001).](image)

![Fig. 7. Interpretation of the quasi-simultaneous X-ray (BeppoSAX) and TeV (CAT) observation of 1997 April 7 and 16 flares of Mkn 501 within the homogeneous SSC model (Tavecchio et al., 2001).](image)

called synchrotron-self Compton (SSC) model since we have two detailed handles on the single electron distribution responsible for both emission components. This test can rule out alternative hadronic models which are less attractive but still viable options for explanation of TeV emission.

• If the SSC model works, it will be possible to fix the key model parameters and calculate the blazar’s intrinsic spectrum, comparing the observed variations of absolute fluxes and spectral shapes with the predictions of self-consistent, time-dependent numerical codes. This is a crucial point because with an estimate of the intrinsic TeV spectrum, then, and only then, we can attempt to estimate the IG-absorption effect by comparing the intrinsic and observed spectra, and thus to get information about CIB.

The observed X/TeV correlations are often interpreted as a strong argument in favor of SSC model, the simplified one-zone version of which generally gives satisfactory fits to the observed X-ray and TeV spectra of Mkn 421 and Mkn 501 (e.g. Mastichiadis and Kirk, 1997; Bednarek and Protheroe, 1999; Kataoka et al., 1999; Krawczynski et al., 2000; Tavecchio et al., 2001, etc.). An example of very good spectral fits for the 1997 April flares of Mkn 501, obtained for fixed “standard” model parameters $\delta_j = 10$ and $B \simeq 0.3$ G and changing only the maximum energy of accelerated electrons, is shown in Fig. 7 (Tavecchio et al., 2001). It should be noticed, however, that the calculation in Fig. 7 do not take into account the IG-absorption of $\gamma$-rays which otherwise results in rather flat intrinsic $\gamma$-ray spectra (Coppi and Aharonian, 1999b; Konopelko et al., 1999; Guy et al., 2000). In particular, any CIB model that predicts NIR fluxes close or higher the CIB reference model no.1 would require unusually hard intrinsic TeV spectrum (Guy et al., 2000) with photon index $\Gamma \leq 1.5$ (see Fig. 3). Such spectra cannot be easily explained by the standard one-zone SSC model without invoking extreme jet parameters like Doppler factors $\delta_j \sim 100$, and very small B-field $B \leq 0.01$ G, which however reduce
the radiation efficiency to an almost unacceptably low level (Krawczynski et al., 2001). The situation is even more difficult for Mkn 421, the X-ray synchrotron cutoff of which never extends beyond 10-20 keV. This significantly limits the freedom for assuming parameters which would allow hard multi-TeV IC spectra.

Despite these difficulties, the leptonic models (perhaps in their more sophisticated versions including the multi-zone SSC and/or External Compton components) remain the generally preferred concept for TeV blazars. These models have two attractive features: (i) the capability of the (relatively) well understood shocks to accelerate electrons to TeV energies (Sikora and Madejski, 2001; Pelletier, 2001) and (ii) effective production of tightly correlated X-ray and TeV γ-ray emission components via the synchrotron and inverse Compton radiation channels (e.g. Ulrich et al., 1997).

The so-called hadronic models are generally lacking in these virtues. These models assume that the observed γ-ray emission is initiated by accelerated protons interacting with ambient mater (Bednarek, 1993; Dar and Laor, 1997; Pohl and Schlickeiser, 2000), photon fields (Mannheim, 1996), magnetic fields (Aharonian, 2000) or both (Mücke and Protheroe, 2001). The models involving interactions of protons with photon and B-fields require particle acceleration to extreme energies exceeding $10^{19}$ eV which is possible if the acceleration time is close to $t_{\text{acc}} = \eta (r_g/c)$ with $\eta \sim 1$ ($r_g$ and $\eta$ are the so-called gyro-radius, and gyro-factor, respectively, $c$ is the speed of light). This corresponds (independent of specific acceleration mechanism) to the maximum (theoretically possible) acceleration rates which hardly can be achieved by the conventional diffusive shock acceleration mechanism (e.g. Pelletier, 2001, Sikora and Madejski, 2001). On the other hand, the undisputed (for any TeV blazar model) condition of high (close to 100%) efficiency of radiative cooling of accelerated particles requires extreme parameters characterizing the sub-parsec jets and their environments, in particular very high (often, almost unrealistic) densities of the thermal plasma, radiation and/or B-fields. But of course, these problems should not prevent us from considering the hadronic models as a viable alternative to the leptonic models.

It should be noticed in this regard that the very fact of strong X/TeV correlations do not yet exclude the hadronic models, because the secondary electrons – the products of interactions of accelerated protons and primary γ-rays – can be readily responsible for the synchrotron X-radiation. Also, some of the hadronic models, for example the synchrotron-proton model can provide not only effective radiative (synchrotron) cooling but also quite good TeV spectral fits. The proton-synchrotron model allows very hard intrinsic TeV spectra and can rather naturally explain the stable spectral shape of TeV radiation of Mkn 501 during strong flares by the self-regulated synchrotron cutoff at $E_{\text{cut}} \simeq 0.3 \eta^{-1} \delta_1$ (Aharonian, 2000). Fig. 8 demonstrates the ability of the synchrotron-proton model to explain the spectra of TeV radiation of Mkn 501 in both the low and high states of the source.

In the proton-synchrotron model we deal with highly magnetized (100 G or so) condensations of γ-ray emitting clouds of EHE protons, where the magnetic pressure dominates over the pressure of relativistic protons. In the SSC models the situation is exactly opposite. The pressure of relativistic electrons is much larger than the pressure of the B-field (Aharonian, 2000; Kino et al., 2001). Surprisingly, for TeV blazars we do not have an intermediate arrangement!

Both the leptonic and hadronic models of TeV blazars pose a number of questions. The answer to some of these question may become possible in the near future. Such an optimistic view is based on the recent progress in the theoretical (time-dependent) studies of characteristics of nonthermal radiation produced in AGN jets, and, of course, on the unique data obtained by RXTE and ground-based γ-ray detectors during the spectacular flares of Mkn 421 in 2001. Importantly, on some occasions positive signals from Mkn 421 were detected also by low-energy air Cherenkov instruments STACEE (Ong et al., 2001) and CELESTE (Le Gallou et al., 2001). These results are obtained at energies around 100 GeV at which the IG-absorption could be safely neglected, and therefore the reported fluxes can be used as “calibration” points when comparing the theoretical predictions with experimental data.

Because Mkn 421 and Mkn 501 are located at almost same distances, we can require that any spectral feature attributed to the IG-absorption be exactly the same for both sources. This is an important circumstance which can help to disentangle the local features in the intrinsic spectra from the contribution induced by interactions with the CIB photons. At the same time it is crucial to have TeV blazars at larger distances, so we can exploit the differences in the spectral modification factors. Fortunately, in addition to Mkn 421 and Mkn 501, presently we do have 4 more TeV blazar candidates – 1ES 2344+5, 1ES 1959+65, PKS 2155-304 and 1ES 1426+428 – located at larger distances (see Fig. 2).
for the CIB model 1 and for the Hubble constant $H_0$ km/s/Mpc and the Hubble constant, the intergalactic absorption effect to the ratio of the CIB flux the parameter which defines the optical depth), in Fig. 10 we show and the shape of the CIB spectrum, this ratio is the only pa-

curve). Hopefully, the future multiwavelength studies may

case of 1ES 1426+428

Because of the relatively large redshift of 1ES 1426+428 ($z = 0.129$), the TeV radiation from this extreme BL Lac object suffers severe IG-absorption. Therefore the discovery of TeV $\gamma$-rays from this source by two independent (VER-ITAS and HEGRA) groups came, to a certain extent, as a pleasant surprise. The spectrum deformation factors calculated for 3 different CIB models show that above 300 GeV the IG-absorption leads to significant steepening of the $\gamma$-ray spectrum, but starting from 1 TeV to several TeV the spectrum is deformed only slightly, although the suppression of the absolute flux may be as large as a factor of 100 (Fig. 9). This effect has a simple explanation discussed in Sec. 3.

Remarkably, the preliminary spectrum of 1ES 1426+428 derived from the HEGRA CT system data taken in 1999 and 2000 (Götting et al., 2001), does show a steep slope at low energies with a tendency for a flattening above 1.5 TeV. The large statistical errors in flux measurements as well as the lack of information about the intrinsic $\gamma$-ray spectrum prevent us from definite conclusions. Nevertheless, in Fig. 10 we show the expected spectra of $\gamma$-rays assuming a single power-law intrinsic spectrum with photon index identical to the index observed by BeppoSAX in the energy region up to 100 keV, $\Gamma = 1.92$ (Costamante et al., 2001). The solid curve represents the absorbed spectrum of $\gamma$-rays calculated for the CIB model 1 and for the Hubble constant $H_0 = 60$ km/s/Mpc. In order to demonstrate the sensitivity of the intergalactic absorption effect to the ratio of the CIB flux and the Hubble constant, $u_{\text{CIB}}/H_0$ (for the given redshift $z$, and the shape of the CIB spectrum, this ratio is the only parameter which defines the optical depth), in Fig. 10 we show the $\gamma$-ray spectra calculated for two other values of the ratio $u_{\text{CIB}}/H_0$ which are 30% less (dashed curve) and 30% more (dot-dashed curve) compared to the the nominal value (solid curve). Hopefully, the future multiwavelength studies may allow us to distinguish between these three curves, thus we could be able to “measure” the absolute CIB flux at NIR, taking into account that the current uncertainty of the the Hubble constant (presumably) does not exceed 30%.

Independent of details, the pure fact of detection of TeV $\gamma$-rays from 1ES 1426+428 is an indicative of a need for revision of the current conceptual view of TeV blazars, according to which the synchrotron (X-ray) peak in the SED dominates over the inverse Compton (TeV) peak (see e.g. Fossati et al. 1998). Indeed, although the detected flux of $\gamma$-rays is only few times $10^{-12}$ erg/cm$^2$s, corrected for IG-absorption this flux may well exceed $10^{-10}$ erg/cm$^2$s. For comparison, the X-ray measurements (Costamante et al., 2001; T. Takahashi, private communication) show fluxes at the level of $10^{-11}$ erg/cm$^2$s. The TeV luminosity significantly exceeds the X-ray luminosity, and apparently this should have an impact on the revision of the current TeV-blazar models.

In particular, for the inverse Compton models (for review see Sikora and Madejski, 2001) this would require that the radiation of electrons occurs in the regime dominated by Compton losses. Interestingly, this could serve as a good argument for justification of the above assumption concerning the single power-law intrinsic TeV spectrum. Indeed, in this regime a pronounced feature (spectral flattening) formed in the steady-state electron distribution (caused by the structure in the Klein-Nishina cross-section) is largely compensated by the same Klein-Nishina effect in the radiated $\gamma$-ray spectrum; thus the $E^{-2}$ type acceleration spectrum of electrons is (almost exactly) transfered to the $\gamma$-ray spectrum (see e.g. Zdziarski and Krolik 1993). Of course, in this case we may expect, within the one-zone SSC model, quite hard synchrotron X-ray spectrum with spectral index $\alpha < 0.5$. This actually does not contradict to the BeppoSAX data for which the broken power-law model gives very flat spectrum with an
index above 10 keV, $\alpha_2 \approx 0.3-0.4$ (Costamante et al., 2001).

The hard intrinsic TeV spectra of 1ES 1426+428 with constant power-law slope and high $L_{\gamma}/L_X \geq 10$ ratio can be explained also by the proton-synchrotron model, assuming that a small, $\approx 0.1$ fraction of the proton-synchrotron TeV $\gamma$-rays suffer internal absorption. If so, the hard X-ray emission could be attributed to synchrotron radiation of the secondary pair-produced electrons (Aharonian, 2000). The weak point of this model is in the requirement of very large, 100 G or so B-field and extremely high acceleration rate of protons.

7 “IR background - TeV gamma-ray crisis”?

From the discussion of the previous section we may summarize that the basic temporal and spectral characteristics of TeV blazars can be described, at least qualitatively, by the current leptonic, and perhaps also hadronic models. At the same time all these models would fail to explain the sharp pile-up which may appear at the end of the “reconstructed” spectrum of Mkn 501, if the reported FIR fluxes correctly describe the level of CIB (see Fig. 3). Motivated by such a non-standard spectral shape, recently several extreme hypotheses have been proposed to overcome the “IR background - TeV gamma-ray crisis” (Protheroe and Meyer 2000). In particular, Harwit et al. (2000) suggested an interesting idea that the HEGRA highest energy events are due to Bose-Einstein condensations interacting with the air atmosphere. Another, even more dramatic hypothesis – violation of the Lorentz invariance – has been proposed to solve this problem (e.g. Kifune, 1999; Stecker and Glashow, 2001). Two more proposals could be added to the list of “exotic” solutions: (i) assuming that Mkn 501 is located at a distance $\ll 100$ Mpc; or (ii) assuming that TeV $\gamma$-rays from Mkn 501 are not direct representatives of primary radiation of the source, but are formed during the development of high energy electron-photon cascades in the intergalactic medium (Aharonian et al. 2001b).

At first glance, both ideas seem relatively “neutral”. But in fact they do contain dramatic assumptions. While first hypothesis implies non-cosmological origin of the redshift of Mkn 501, the second hypothesis requires extremely low intergalactic magnetic field of order of $10^{-18}$ G or less.

Although very fascinating, the appeal for revisions of essentials of modern physics and astrophysics seems to be too premature. The nature of the FIR isotropic emission detected by COBE is not yet firmly established, and it is quite possible that the bulk of the reported flux, especially below 100 $\mu$m, is a result of superposition of different local backgrounds. It should be noticed, however, that not only the flux at 60$\mu$m, but also the CIB fluxes at longer, $\lambda \geq 100\mu$m wavelengths are responsible (albeit in a less distinct form) for the appearance of the pile-up, unless we assume very specific CIB spectrum in the MIR-to-FIR transition region (Aharonian et al., 1999a; Coppi and Aharonian, 1999b; Guy et al., 2000; Renault et al., 2001). Therefore it is important to explore other possibilities for formation of pile-ups in the spectra of TeV blazars. Motivated by this, recently we have proposed a new, non-acceleration scenario which postulates that the $\geq 10$ TeV radiation of Mkn 501 is a result of the bulk motion Comptonization of ambient low-frequency photons by a cold ultrarelativistic conical wind (Aharonian et al., 2002).

The relativistically moving plasma outflows in forms of jets or winds, are common for many astrophysical phenomena on both galactic or extragalactic scales. Independent of the origin of these relativistic outflows, the concept of the jet seems to be the only successful approach to understand the complex features of nonthermal radiation of Blazars, Microquasars and GRBs. The Lorentz factor of such outflows could be extremely large. In particular in the Crab Nebula the Lorentz-factor of the MHD wind is estimated between $10^6$ and $10^7$ (Rees and Gun, 1974; Kennel and Coroniti, 1984). Meszaros and Rees (1997) have shown that in the context of cosmological GRBs the magnetically dominated jet-like outflows from stellar mass black holes may attain extreme Lorentz factors exceeding $10^9$. The conventional Lorentz factors of jets in the inverse Compton models of $\gamma$-ray blazars, are rather modest, $\Gamma \sim 10$. However there are no apparent theoretical or observation arguments against the bulk motion with much larger Lorentz-factors (see e.g. discussion by Celotti et al., 1998). Because of existence of dense photons fields in the inner sub-parsec region of sources like Mkn 421 and Mkn 501, the Compton optical depth $\tau_C$
could be as large as 1. Obviously, for our model the most favorable value for $\tau_C$ lies between 0.1 (in order to avoid huge energy requirements to the outflow) and 1 (in order to avoid the Compton drag). In particular, we have to assume that in the proximity of the black hole the outflow should be Poynting flux dominated, and only at large distances from the central object, where the photon density is significantly reduced, the major part of the electromagnetic energy is transferred to the kinetic energy of bulk motion.

Due to the extremely large Lorentz factors exceeding $10^7$, the Compton scattering on the ambient NIR/optical photons with energy more than 1 eV proceeds in deep Klein-Nishina regime; therefore the $\gamma$-radiation should have a very narrow distribution with energy $E \approx E_0 = m_e c^2 \Gamma$. Meanwhile, the IC scattering on ambient far IR photons surrounding the central source, still takes place in the Thomson regime, and thus results in a smooth broad-band spectrum.

Fig. 11 demonstrates that the overall absorption-corrected (for the CIB at FIR close to the extreme CIB model no.3) spectrum of Mkn 501 can be satisfactorily explained in the terms of the inverse Compton emission of the cold jet with bulk Lorentz factor $\Gamma = 3.33 \times 10^2$, assuming an ambient radiation field with a narrow (Planckian) type radiation with temperature $kT = 2 eV$ (dashed curve I). The dashed curve II which formally is the residual from the subtraction of the unshocked wind component radiation from the intrinsic (reconstructed) TeV emission (solid heavy line), can be attributed to the bulk Comptonization on ambient far IR photons produced e.g. by cold clouds surrounding the source. Alternatively, the “residual component” (curve II) can be referred to the SSC (or any other) radiation component of blobs in shocked jet. This two-stage (pre-shock plus post shock) scenario of formation of TeV $\gamma$-ray emission is schematically illustrated in Fig. 12.

The possibility to disentangle the multi-TeV emission with a characteristic sharp pile-up at the very end of the spectrum, $E_\gamma \approx m_e c^2 \Gamma$, from the sub-10 TeV emission associated with the shocked structures (e.g. blobs) in the jet, not only solves the possible “IR background – TeV gamma-ray crisis” but also allows more relaxed parameter space for interpretation of X-rays and the remaining “low” energy ($\leq 10$ TeV) $\gamma$-rays within the conventional SSC scenario. Consequently, this offers more options for interpretation of X-ray/gamma-ray correlations. If the overall TeV radiation of Mkn 501 indeed consists of two, unshocked and shocked jet emission components, we may expect essentially different time behaviors of these components. In particular, the “unshocked jet” ($\geq 10$ TeV) component should arrive earlier than the SSC components consisting of synchrotron X- and sub-10 TeV IC $\gamma$-rays. Therefore, an important test of the suggested two stage scenario of the TeV radiation of jets would be the search for correlations (or lack of such correlations) of $\geq 10$ TeV radiation with both the low energy (e.g. 1-3 TeV) $\gamma$-rays and synchrotron X-rays. The low statistics of (heavily absorbed) $\gamma$-rays above 10 TeV makes the search for such correlations rather difficult, and requires ground-based instruments with huge, $\gg 0.1$ km$^2$ detection areas in this energy domain. The new generation IACT arrays like CANGAROO-3, H.E.S.S. and VERITAS should be able to perform such correlation studies.

It should be noticed, however, that the study of the signatures of IG-absorption of $\gamma$-rays from Mkn 421 and Mkn 501 does not contain adequate information about CIB at $\lambda \geq 40 \mu$m. This information is essentially lost due to the heavily absorbed $\gamma$-rays above 20 TeV. This objective is rather contingent on discovery of nearby extragalactic TeV sources within ~50 Mpc, dictated by the condition that the mean free path of $\gamma$-rays at these energies should not significantly exceed the distance to the source (see Fig. 2). Despite the lack of very close blazars, other potential extragalactic $\gamma$-ray sources like the nearby radiogalaxies Centaurus A and M 87, and perhaps also the starburst galaxies Arp 220, M 82 and NGC 253 may (hopefully) provide us with multi-TeV $\gamma$-rays for such important studies.

Yet, the distant TeV sources may offer an additional, and perhaps even more informative channel for derivation of CIB fluxes at FIR wavelengths. Such a possibility is based on the study of angular and spectral characteristics of hypothetical giant Pair Halos expected around powerful nonthermal extragalactic sources (Aharonian et al., 1994).
8 Pair Halos and CIB

Because of IG-absorption, the bulk of primary TeV γ-rays from distant extragalactic sources is not visible. The energy of these photons however is not lost – the electromagnetic cascade initiated by the absorbed γ-rays can be observed! The cascade in the IG medium (e.g. Berezinsky and Kudrintsev, 1990; Protheroe and Stanev, 1993; Coppi and Aharonian, 1997) is supported by 2 processes: (i) by inverse Compton scattering on the photons of 2.7 K MBR and (ii) by photon-photon pair production on CIB (for energies above 100 TeV - also on 2.7 K MBR). When the magnetic field near the source is sufficiently large, $B \gtrsim 10^{-6}$ G (generally on the scales of tens of Mpc, but if the spectrum of primary γ-rays extends into PeV region - within tens of kpc), i.e. when the mean free path of cascade electrons (at least at the initial stages) is large compared to Larmor radii, the cascade will generate, even for a highly beamed primary source, an extended isotropic Pair Halo (see Fig. 13). While the formation of Pair Halos is unavoidable for all extragalactic objects with spectra extending beyond 10 GeV, only relatively compact Pair Halos formed around (multi) TeV sources could be detectable. The superposition of the cascade radiation of all Pair Halos formed in the Universe may contribute significantly to the diffuse GeV γ-ray background (Coppi and Aharonian, 1997).

The halo radiation can be distinguished by its characteristic variation in spectrum and intensity with angular distance from the central source, which weakly depends on the details of the source model, in particular on the energy spectrum and the geometry of the primary source, especially when a hard primary γ-ray spectrum extends to PeV energies.

The energy $E_{\gamma}$ and the arrival angle θ of the detected photon from a source at a distance $d$ are determined, on average, by the energy of the parent electron $E_e \approx (E_{\gamma}/4kT_0)^{1/2}m_e c^2$ ($T_0 = 2.7$ K), and the distance $l$ from the central source where this electron is produced. Because the mean free path of γ-rays $\Lambda$ decreases with energy (see Fig. 2), the energy and site of production of the secondary electron are defined, on average, by the “last γ-CIB interaction” $E_e \approx E_{\gamma,0}/2$, therefore the energy $E_{\gamma}$ and arrival angle θ of the detected γ-rays contain information about their “grandparents” - γ-rays with energy $E_{\gamma,0} \approx 34(E_{\gamma}/1$ TeV)$^{1/2}$ TeV, and mean free path $\Lambda(E_{\gamma,0}) = d \cdot \theta$. Correspondingly, the measured mean free path $\Lambda(E_{\gamma,0})$ should tell us about the density of CIB at $\lambda \sim 50(E_{\gamma}/1$ TeV)$^{1/2}$ μm. Thus, detections of Pair Halos surrounding Mkn 421 and Mkn 501 at 1 TeV should provide information on CIB around 50 μm, provided that the primary spectrum extends beyond 30 TeV.

Recently the HEGRA collaboration made the first attempt to probe the existence of a Pair Halo in direction of Mkn 501, using the data base accumulated during the period of observations from 1997 to 1999 (Aharonian et al., 2001c). The derived limit on the halo flux $J_{\gamma \nu}(\geq 1$ TeV) $\sim 10^{-6}$ ph/cm$^2$s sr within 1° is unfortunately above the theoretical expectations based on the energy budget constraints. Indeed, Mkn 501 actually is not an ideal candidate for a halo source given its relatively modest luminosity and the fact that the preferable distance to observe halo is in the range of several 100 Mpc to 1 Gpc; consequently, the most effective searches can be performed by detectors with energy threshold around 100 GeV (Aharonian et al., 1995). In this regard, the BL Lac objects 1ES 1426+428 at $z = 0.129$ and PKS 2155-30 at $z = 0.116$ with γ-ray luminosities exceeding the “quiescent” TeV luminosity of Mkn 501 at least by a factor of 10, seem to be more suitable objects for producing detectable Pair Halos. The forthcoming H.E.S.S. array of 10m IACTs equipped with optimal for this purpose 5° FoV high resolution cameras, will be the first instrument for a sensitive search for Pair Halos at $z \sim 0.1 - 0.2$.

Generally, the blazars are are relatively weak sources – they seem very bright because of the Doppler boosting (proportional to $\delta^4 \geq 10^3$). The distant powerful radiogalaxies and quasars with large-scale jets (as potential accelerators of ultrahigh energy cosmic rays) may appear more promising sites for production of detectable - strong and compact - Pair Halos (Aharonian, 2002). The detection and identification of such halos from cosmologically distant objects beyond $z = 1$ is possible at energies of γ-rays of about 10 GeV. While the spectral cutoffs in the energy spectra of the direct and halo emission components are caused by absorption in the diffuse UV background radiation, the angular size of the halo contains information about the CIB at several to 10 μm wavelengths at the epoch corresponding to the redshift of the central source $z$. This is a unique (not available by other means) channel which provides us with model-independent information about the cosmological evolution of CIB. Such studies can be effectively performed by GLAST (e.g. Gehrels and Michelson 1999) and by future sub-10 GeV threshold high-altitude IACT arrays like 5@5 (Aharonian et al. 2001).

9 Summary

The energy-dependent mean free path of γ-rays in the intergalactic medium at TeV energies does not exceed several 100 Mpc. Therefore VHE γ-rays from TeV blazars arrive with significantly distorted spectra. Our limited knowledge of CIB results in large uncertainties in the reconstructed (cor-
rected for intergalactic absorption) intrinsic \(\gamma\)-ray spectra. Consequently, in spite of good quality of spectral measurements of two strongest TeV blazars, Mkn 421 and Mkn 501, nowadays we are faced with a challenge - our understanding of radiation processes in relativistic jets is neither complete nor conclusive. Nevertheless, the gamma-ray astronomers believe that eventually (soon ?) they will learn to identify confidently the radiation mechanisms, to fix/constrain the relevant model parameter space, and calculate robustly the intrinsic \(\gamma\)-ray spectra based on the multiwavelength studies of spectral and temporal characteristics of blazars obtained simultaneously at X-ray and TeV bands on sub-hour timescales. Then it will be possible to estimate unambiguously the effect of the intergalactic \(\gamma\)-ray absorption, and thus to infer robust information about the CIB fluxes. Moreover, the studies of angular and spectral properties of giant Pair Halos formed around powerful extragalactic multi-TeV sources may provide us with a unique tool for derivation of the spectra and absolute fluxes of CIB at different cosmological epochs \(z\), and thus to probe the evolution of the galaxies in past.

References

Aharonian F.A., 2002, MNRAS, to appear in MNRAS
Aharonian F.A., Timokhin A., Plyashevshnikov A.V., 2002, to appear in A&A
Aharonian F.A. et al., 2001, Astropart. Physics, 15, 335
Aharonian F.A. et al. (HEGRA collaboration), 2001a, A&A 366,62
Aharonian F.A. et al. (HEGRA collaboration), 2001b, ApJ,546,898
Aharonian F.A. et al. (HEGRA collaboration), 2001c, A&A,366,746
Aharonian F.A., 2000, New Astronomy, 5, 377
Aharonian F.A. et al. (HEGRA collaboration), 1999a, A&A,349,11
Aharonian F.A. et al. (HEGRA collaboration), 1999b, A&A,350,757
Aharonian F.A. et al., 1995, Proc. 24th ICRC, Rome, vol. 2, 2622
Aharonian F.A., Coppi P.S. and Volk H.J., 1994, ApJ,423, L5
Bednarek W., 1993, ApJ, 402, L29
Bednarek W. and Protheroe J.R., 1999, MNRAS, 310, 577
Berezinsky V. S. and Kudriaevtsev V. A., 1990, ApJ, 349, 620,
Cambresy L. et al., 2001, ApJ, 555, 563
Catanese M. et al., 1998, ApJ, 501, 616
Celotti A., Fabian A.C., Rees M.J., 1998, MNRAS, 293, 239
Chadwick P. et al., 1999, Astropart. Physics, 11, 145
Coppi P.S. and Aharonian F.A., 1999a, ApJ, 521, L33
Coppi P.S. and Aharonian F.A., 1999b, Astropart. Physics, 11, 35
Coppi P.S. and Aharonian F.A., 1997, ApJ, 487, L9
Costamante L. et al., A&A, 371, 512
Dar A. and Laor A., 1997, ApJ, 478, L5
De Jager O.C. and Stecker F.W., 2001, to appear in ApJ
Djannati-Atai A. et al., 1999, A&A, 350, 17
Dwek E. and Arendt R.G., 1998, ApJ, 508, L9
Finkbeiner D.P., Devis M. and Schlegel D.J., 2000, ApJ, 544, 81
Fossati G., Jordan M. and Buckley J., 2001, in: "Gamma-ray Astrophysics 2001", AIP Conf. Series, in press
Fossati G., et al., 1998, MNRAS, 298, 433
Franceschini A. et al., 2001, A&A 378, 1
Gaidos J.A. et al., 1996, Nature, 383, 319
Gehrels N. and Michelson P., 1999, Astropart. Phys. 11, 277
Gorjian V., Wright E.L., Chary R.R., 2000, ApJ, 536, 550
Gould R.J. and Schreder, G.P., 1966, Phys. Rev. Letters, 16, 252
Götting N. et al. (HEGRA collaboration), talk presented at 27th ICRC, Hamburg
Guy J. et al., 2000, A&A, 359, 419
Hauser M.G and Dwek E., 2001, ARA&A, 39, 249
Hauser M.G. et al., 1998, ApJ, 508, 25
Hofmann W., 2000, Astropart. Phys., 12, 207
Horan D. et al., 2001, Proc. 27th ICRC, Hamburg, vol. 7, 2622
Horns D. et al. (HEGRA collaboration), talk presented at 27th ICRC, Hamburg
Jelley J.V., 1966, Phys. Rev. Letters, 16, 479
Kataoka J. et al., 1999, ApJ, 514, 138
Kenne C.F. and Coroniti F.V., 1984, ApJ, 283, 694
Kifune T., 1999, ApJ, 518, L21
Kino M., Takahara F. and Kusunose M., 2001, to appear in ApJ
Konopelko A. K. et al., 1999, ApJ, 518, L13
Krawczynski H. et al., 2000, A&A, 353, 97
Krawczynski H., et al., 2001, in preparation
Krennrich F. et al., 2001, ApJ, 560, L45
Lagache G et al., 1999, ARA&A, 39, 249
Mannheim K., 1998, Science 279, 684
Maraschi L. et al., 1999, Astropart. Physics, 11, 189
Mastichiadis A. and Kirk J.G., 1997, A&A, 320, 19
Matsumoto T., 2000, The ISAS Science Report SP No. 14, p. 179
Meszaros P. and Rees M.J., 1999, ApJ, 482, L29
Mücke A. and Protheroe R. J., 2001, Astropart. Physics, 15, 121
Nikishov A.I., 1962, Sov. Phys. JETP, 14, 393
Nishiya T. et al., 1999, 26th ICRC (Salt Lake City), vol. 3, 370
Ong R. et al., 2001, talk presented at 27th ICRC, Hamburg
Pian E. et al., 1998, ApJ, 492, L17
Pohl M. and Schlickeiser R., 2000, A&A, 354, 395
Pozzetti L. et al., 1998, MNRAS, 298, 1133
Primack J.R. et al., 2001, in: High Energy Gamma-Ray Astronomy
(eds. F.A. Aharonian and H.J. Völk), AIP Conf Ser. 558, 463
Primack J.R. et al., 1999, Astropart. Physics, 11, 93
Protheroe R.J. and Meyer H., 2000, Physics Letters B, 493, 1
Protheroe R.J. and Stanek T., 1993, MNRAS, 264, 191
Punch M. et al., 1992, Nature, 358, 477
Rees M.J. and Gun J.E., 1974, MNRAS, 167, 1
Renault C. et al., 2001, A&A, 371, 771
Sambruna R. et al., 2000, ApJ, 538, 127
Schlegel D.J., Finkbeiner D.P. and Devis M., 1998, ApJ, 500, 525
Sikora M. and Madejski G., 2001, in: High Energy Gamma-Ray Astronomy AIP Conf Ser. 558, 275
Stecker F.W. and Glashow S. L., 2001, Astropart. Physics, 16, 97
Stecker F.W., De Jager O.C. and Salamon M.H.,1992, ApJ, 390, L49
Takahashi T. et al., 2000, ApJ, 542, L105
Tavecchio F. et al., ApJ, 2001, 554, 725
Ulrich M.H., Maraschi L. and Urry C.M., 1997, ARA&A, 35, 445
Vassiliev V., 2000, Astropart. Physics, 12, 217
Wright E.L. and Johnson D.B., 2001, to appear in ApJ
Zdziarski A. K. and Krolik J.H., 1993, ApJ, 409, L33
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