JETS ON ALL SCALES

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Received Day Month Year
Revised Day Month Year
Communicated by Managing Editor

A brief overview of jets and their central drivers is presented, with a focus on accreting black hole systems. In particular, scaling relations that elucidate some basic properties of the engines are derived, and the implications for the associated outflows are discussed. The kinematics and dynamics of relativistic jets in various systems and the dissipation of their bulk energy is considered, with an emphasis on consequences of recent observations. Also considered is the interaction of the jets with their environment. Comments on multi-messenger probes are made at the end.

Keywords: Jets; blazars; microquasars; gamma-ray bursts

1. Introduction

Advances of observational techniques and improvements in numerical capabilities in the last decade or so have led to a progress in our understanding of astrophysical jets and their drivers, but also raised new and highlighted some old questions, mainly with regards to the micro-physics involved. For instance, the physics of accretion, the details of the Blandford-Znajek mechanism, the acceleration of ideal MHD outflows, the physics of collisionless shocks and the role of relativistic radiation mediated shocks are better understood now then a decade ago. On the other hand, the loading and dissipation of magnetically dominated flows, the generation of magnetic fields behind shocks, as implied by observations of afterglow emission in GRBs, the role of relativistic turbulence in and its effects on the dynamics of the expanding flow, and the nature of the compact object in certain systems are but some examples of open questions that only very recently have started to be examined systematically using advanced tools. We are still lacking any knowledge of the composition of relativistic jets in almost all sources, do not understand yet how magnetic flux is advected from large radii all the way into the very inner regions of the disk in AGNs and microquasars (or is it produced locally by some mechanism? e.g., a Poynting-Robertson battery), are puzzled by the detection of UHECRs, and hope for detection of VHE neutrinos from the jets and gravitational waves from their engines that will shed a new light on some of these open questions.
Below is a brief summary of some of these issues, that reflects my naive perception of the field.

2. Central Engine

A common view is that the launching of astrophysical jets involves a rotating, magnetized driver. In compact relativistic systems the central engine may consist of a magnetized neutron star, as in the case of pulsars, γ-ray binaries, and magnetars, or an accreting black hole, as in blazars, microquasars and some classes of GRBs. The following discussion focuses on accreting black hole systems.

2.1. Scaling of conditions in the disk

Two important parameters control the conditions in the inner regions of a disk surrounding an accreting black hole: the mass of the black hole, henceforth measured in units of solar mass, $m_{BH} = M_{BH}/M_\odot$, and the accretion rate $\dot{m}$, rendered dimensionless by measuring in Eddington units $\dot{M}_{Edd} = L_{Edd}/c^2$. The temperature, density and magnetic field strength scale with the ratio $\dot{m}/m_{BH}$ as

$$T_d = 10^7 (\dot{m}/m_{BH})^{1/4} (r/3r_s)^{-3/4} \text{ K},$$

$$\rho_d = 10^{-6} \alpha^{-1} (\dot{m}/m_{BH})(r/3r_s)^{-3/2} \text{ gr cm}^{-3},$$

$$B = 10^{8.5} (\xi_B \dot{m}/m_{BH})^{1/2} \text{ G}.$$  

The two additional parameters that appear in the above scaling, the viscosity parameter $\alpha$ and the magnetization $\xi_B$, represent parametrization of poorly understood micro-physics. Numerical simulations seem to indicate that their values are essentially independent of $\dot{m}$ and $m_{BH}$ and span a rather narrow range.

The choices of canonical values $\dot{m} = 1$, $m_{BH} = 3$ and $\dot{m} = 1$, $m_{BH} = 10^8$, representing a prototypical microquasar and a prototypical blazar, respectively, yield disk temperatures that are consistent with the peak of the SED. For GRBs, with $\dot{m} = 10^{15}$, $m_{BH} = 3$, a disk temperature of a few MeV and a density exceeding $10^{10}$ gr cm$^{-3}$ is anticipated. In this regime the weak interaction time scale becomes comparable to the accretion time and the inner regions of the disk cools via emission of MeV neutrinos, and may contain neutron rich material. A neutron-to-proton ratio in excess of 20 can be reached under certain conditions in the innermost regions. If picked up by the GRB producing jet, such a neutron rich composition may have important consequences for the loading of the flow and for the prompt emission mechanism. Whether the outflow can remain neutron rich as it accelerates to high Lorentz factors is yet an open issue. It could well be that the flow is multi-component, consisting of an ultra-relativistic core ensheathed by a slow neutron rich wind. Leaking of free neutrons (that can easily cross magnetic field lines) from the slow wind into the baryon poor core can initiate a nuclear avalanche that leads to baryon loading of the inner flow and dissipation of its bulk energy. A hard gamma-ray and neutrino spectrum is then expected.
2.2. The disk-outflow connection

MHD simulations seem to indicate that magnetic launching of a relativistic outflow in accreting black hole systems requires the presence of a Kerr BH with a specific angular momentum $\tilde{a}$ not much smaller than unity. Turbulence in the disk leads to a rapid redistribution of magnetic field lines and substantial mass loading, and so outflows from the disk are expected to be slow, unlike the Blandford-Payne solutions.

The power that can, in principle, be extracted magnetically from a rotating black hole can be expressed as

$$L_j = 10^{21} \epsilon \tilde{a}^2 B^2 m_{BH}^2 \text{ erg s}^{-1},$$

where $\tilde{a}$ is the specific angular momentum of the hole, and $\epsilon$ is a parameter that depends on magnetic field geometry and other details. By employing (3) a simple relation between the accretion rate and outflow power is obtained:

$$L_j = (\xi_B \epsilon \dot{m}) L_{Edd}. \quad (5)$$

This scaling appears to be consistent with the outflow power inferred in different classes of sources. However, the correlation between outflow ejection and spectral states in X-ray binaries reveals high accretion states during which the outflow is strongly suppressed, suggesting that additional effects may be involved.

The disk luminosity has a similar scaling,

$$L_d = (\xi_r \dot{m}) L_{Edd}, \quad (6)$$

here $\xi_r$ is the radiative efficiency of the accretion flow. The presence of powerful $\gamma$-ray flares in some blazars suggests that in some circumstances the accretion mode is radiative inefficient. An example is the extreme flare reported for PKS 2155-304. The flare duration, $t_{var} = 300$ sec, and the isotropic equivalent luminosity, $L_{TeV} \gtrsim 10^{46}$ erg s$^{-1}$, imply

$$L_j > f_b L_{TeV} \simeq 10^{44} \theta^2 \bar{1}_{-1} L_{TeV,46} \text{ erg s}^{-1}, \quad (7)$$

with $f_b = \theta^2/2$ denoting the beaming factor of the emission for a two-sided conical jet with an opening angle $\theta = 0.1 \theta_{-1}$. To avoid $\gamma\gamma$ absorption of the observed TeV photons by the disk radiation at small radii, that would smear out any rapid variations, requires either unusual beaming, or low radiative efficiency $\xi_r \lesssim 10^{-3}$ for typical opening angles.

Perhaps the best example of radiative inefficient accretion is M87. Various estimates of the jet power yield $L_j \gtrsim 10^{44}$ erg/s (see Ref. 8 for a summary of published estimates), implying $\dot{m} \sim 10^{-2}$. The bolometric luminosity, on the other hand, is smaller by a factor of $10^{-3}$, suggesting $\xi_r \lesssim 10^{-3}$. It is worth-noting that the luminosity emitted from the jet itself is a small fraction of the jet power, so this object is in fact a good example of a “dark” source. This seems to be quite common among BL Lac sources. Whether powerful, dark blazars are present in the nearby Universe is a question of interest in connection with potential UHECRs sources, as explained below.
3. Jets

3.1. Kinematics and dynamics

The best indication that jets associated with compact astrophysical systems are relativistic is of course the measurement of superluminal motions, which reflect the speed of some pattern, not necessarily the fluid, that propagates down the jet. The range of values inferred for the associated Lorentz factors is $\Gamma \sim 1 - 50$ in blazars and $\Gamma \sim 1 - 10$ in microquasars.

Constraints on the Lorentz factor of emitting fluid are commonly derived using opacity arguments. Those are mainly applied to GRBs and blazars in which the contribution of ambient radiation can be neglected on relevant scales. If both the gamma-rays and the target photons are produced isotropically inside a source moving at a Lorentz factor $\Gamma$, e.g., by synchrotron and SSC mechanisms, then both components will be beamed into a cone of opening semi angle $\theta \sim \Gamma^{-1}$ in the star frame.

Two factors then lead to suppression of the pair production opacity: firstly, the flux factor, as measured in the star frame, satisfies $(1 - \cos \theta) \sim 1/(2\Gamma^2)$. Secondly, the threshold condition implies that only target photons having energy $\epsilon_s > 4\Gamma^2/\epsilon_\gamma$ can absorb a $\gamma$-ray photon of energy $\epsilon_\gamma$ (energies are measured in units of $m_ec^2$), and so the number density of target photons above the threshold is $n_s(\epsilon_s) = K(\epsilon_s^{-\alpha})$. The pair production optical depth then scales as $\tau_{\gamma\gamma} \propto \Gamma^{-2(\alpha+1)}$. Now, the size of the emission zone $r_{em}$ may be constrained by variability of the observed flux. For a relativistic source $r_{em} \lesssim \Gamma^2\Delta t/c$, where $\Delta t$ is the shortest variability time observed at energy $\epsilon_\gamma$. The requirement that $\tau_{\gamma\gamma} < 1$ at $r = r_{em}$ then yields, assuming $K(\epsilon_s) = K_0(\epsilon_s/r_0)^{-2}$,

$$\Gamma > \Gamma_{min} = \left(\frac{3\pi K_0 A(\alpha)}{8\Delta t}\right)^{1/(2\alpha+4)} \epsilon_\gamma^{\alpha/(2\alpha+4)}$$  \hspace{1cm} (8)

where $A(\alpha)$ is a numerical factor that depends on the exponent $\alpha$, and is given in Ref.\cite{9} For typical values of $\alpha A(\alpha)$ lies in the range 0.1-0.2. The observables $\epsilon_\gamma, \Delta t$ and the observed luminosity that fixes $K_0$ impose a constraint on $\Gamma$. Such opacity arguments have been applied to GRBs, whereby $\Gamma \sim 10^3$ \cite{10} has been inferred in the most extreme cases, and to TeV blazars \cite{11}, where $\Gamma > 50$ have been estimated for several sources.

What mechanism accelerates the flow to such high Lorentz factors? Magnetic acceleration is one possibility. In general it is not very effective in the sense that the flow remains asymptotically Poynting dominated. For a split monopole $\Gamma_\infty \simeq \sigma^{1/3}$ where $\sigma$ is the ratio of magnetic to kinetic energy at the base of the flow. However, it has been shown recently that causal sections can be magnetically accelerated up to equipartition where $\Gamma_\infty \sim \sigma^{12/13}$. In case of GRBs the opening angle naively anticipated for the asymptotic flow, $\theta \lesssim \Gamma^{-1}$, seems to be significantly smaller than those inferred from observations. The latter condition may be alleviated in outflows that break out of a star \cite{14} as anticipated in long GRBs. We note that $\Gamma \sim 10^3$ has been reported recently for some short bursts (e.g., GRB090510).
In outflows having a large Thomson depth the radiation is strongly coupled to the plasma. If the entropy per baryon at the base of the flow is large then the flow can radiatively accelerate to a large terminal Lorentz factor $\Gamma_\infty$ that depends on the location of the photosphere with respect to the coasting radius. For a burst of total energy $E$ and baryon mass $M_b$ the terminal Lorentz factor is $\Gamma_\infty \simeq E/M_b c^2$ if the photospheric radius $r_{ph}$ is larger than the coasting radius $r_c$. In the opposite limit, $r_{ph} < r_c$, the terminal Lorentz factor roughly satisfies $\Gamma_\infty \simeq \Gamma_0 (r_{ph}/R)$, where $\Gamma_0 \simeq 1$ is the Lorentz factor at the base of the outflow, at $r = R = 10^6 R_6$ cm. At the critical loading for which $r_{ph} = r_c$ the asymptotic Lorentz factor is given by

$$\Gamma_c \simeq 1.8 \times 10^3 L_{52}^{1/4} R_6^{-1/4},$$

with $L_{52}$ being the isotropic equivalent luminosity in units of $10^{52}$ erg s$^{-1}$. Detection of sources that violate this limit would strongly support magnetic acceleration. For GRB 080916C we estimate $\Gamma_c \sim 5500$.

### 3.2. Dissipation

Dissipation of the outflow bulk energy occurs over a large range of scales. It can be accomplished through overtaking collisions of fluid shells (internal shocks), as a result of interactions of the outflow with a surrounding medium (e.g., recollimation shocks, breakout shocks, blast waves) or, in magnetically dominated regions, due to magnetic reconnection and/or instabilities.

Shocks that form by overtaking collisions can dissipate energy at radii $r_d > \Gamma^2 c \delta t$, where $\Gamma$ is the Lorentz factor of the slow shell and $\delta t \geq r_s/c$ is the duty cycle of the intermittent engine. In blazars and microquasars with $\Gamma \sim 1 - 50$ dissipation by internal shocks is expected close to the BH, consistent with (but not necessarily implied by) the short durations of strong flares observed in these objects, particularly in TeV blazars.

In GRBs $r_d > 10^3 r_s$ or so for the Lorentz factors envisaged. For the shocks to form above the photosphere $\Gamma > 200 L_{52}^{1/5} \delta t_{-3}^{-1/5}$ is required, where $\delta t_{-3} = \delta t/(1 \text{ ms})$. In case of GRB 080916C, for which $L_{52} \sim 100$ was measured during the first few seconds, this implies $\Gamma > 800$ in order that the prompt emission be produced in optically thin regions. This value is comparable to the limit derived using opacity constraints on the highest GeV photons recorded, as explained above. Thus, it seems that in this burst a sizable fraction of the available energy may dissipate slight above or just below the photosphere, in regions of modest Thomson depth, $\tau \sim 1 - 10^2$. Shocks that form above the photosphere are expected to be collisionless. These can Fermi accelerate particles and produce nonthermal spectra with a modest efficiency. Shocks that form below the photosphere, where the Thomson depth exceeds unity, are mediated by Compton scattering. Under conditions anticipated in GRBs these shocks convect enough radiation upstream to render photon production in the shock transition negligible. Bulk Comptonization then produces a broad, nonthermal component in the immediate downstream that extends up to a fraction
of the KN limit in the shock frame, depending on details (or up to a fraction of $\sim \Gamma m_e c^2$ in the observer frame). At what depth thermalization is established is yet an open issue. We naively expect the spectrum to be quasi thermal if the Lorentz factor is sufficiently small to allow shocks to form well below the Thomson sphere, and nonthermal if a considerable fraction of the energy dissipates in a region where the Thomson depth is modest (less than a few hundreds). According to this interpretation the lack of a thermal component in the prompt emission from GRB 080916C implies that shocks are produced by radiation mediated shocks that form at a modest Thomson depth, consistent with the limit derived on the Lorentz factor. Alternatively, the shocks are collisionless. The recent detections of some bursts that exhibit a prominent thermal component suggests that in those sources dissipation occurred deep enough below the photosphere, on thermalization scales. The nonthermal extension requires additional dissipation above or just below the photosphere.

### 3.3. Interaction with the Environment

The environment plays an important role both through direct interactions with the jet and/or by screening the jet emissions. Collimation and blast waves/cocoons are generic environmental signatures in all sources. This interaction may provide an important heating mechanism of IGM gas in clusters.

In microquasars associated with a massive companion the hydrodynamic and emission from the jet may be dominated by interactions with the wind and radiation from the stellar companion (for a review see Ref. 18 and references therein). Even the nature of the compact object in at least two TeV microquasars, LS 5039 and LS 1+61 303, is controversial 18. The recent detection of GeV emission 19,20 from these two sources clearly indicates two components, one that peaks at a few GeV and a second one extending to TeV energies. Both components show modulations consistent with the orbital motion of the binary system (with a phase difference between the peak flux of each of the components), indicative of the interaction with the companion star. In both objects the modulation of the GeV emission appears to be consistent with IC scattering of the companion’s radiation; the suppression of the TeV flux during the peak of the GeV emission may be due to enhanced pair production opacity. Alternatively, the GeV emission may originate from a pulsar magnetosphere 20, however, in this case the modulation of the flux requires additional explanation.

In long duration GRBS the jet interacts with the putative stellar envelope. A successful event requires breakout of the jet from the star. Owing to the scaling of the velocity at which the jet head advances with the expelled power, a successful breakout favors low power jets (for a given explosion energy), so that it could well be that in case of GRBs associated with collapsars long events are pre-selected by the environment. Failed GRBs may have a different appearance. In particular, an orphan burst of VHE neutrinos may be a unique diagnostic of choked outflows 21.
provided the Lorentz factor of the hidden jet is sufficiently high to render internal shocks that form in the jet collisionless, which is required for efficient acceleration of the protons that interact with the radiation produced behind the bow shock.

The subsequent interaction of the jet with a stellar wind or ISM produces a relativistic blast wave. The post-prompt emissions observed in most long GRBs are most likely produced in the thin layers enclosed between the forward and reverse shocks, and are important diagnostics of the blast wave evolution and the conditions in the shocked layers. Although a simple blast wave model has been quite successful in explaining the late afterglow evolution, recent observations raise some questions. In particular, (i) observations of the late afterglow emission indicate strong amplification of magnetic fields in the post shock region - by several orders of magnitudes larger than what can be achieved by compression of the ambient magnetic field. Kinetic instabilities have been proposed as the origin of these magnetic fields, however, whether the resulting fields can be maintained over sufficiently large scales is yet an open issue. An alternative is amplification by turbulence. (ii) SWIFT observations during the early afterglow phase reveal strong deviation of the lightcurve at early times from that predicted by the simple blast wave model. Several ad hoc explanations have been offered, including prolonged activity of the central engine and evolution of microphysical parameters. However, the feasibility of these scenarios depends on poorly understood physics, and it remains to be demonstrated that they can be derived from first principles. (iii) In the fireball scenario commonly adopted, the naive expectation has been that the crossing of the reverse shock should produce an observable optical flash. Despite considerable observational efforts, such flashes seem to be very rare. It could be that the ejecta is magnetically dominated, though it is not clear at present how a thin magnetic shell can reach such large radii without expanding considerably. Moreover, some accumulation of baryon rich matter at the ‘piston’s’ head is anticipated during the shock breakout phase, that may mimic effects of a hydrodynamic ejecta.

Recently, it has been shown that the contact discontinuity of the decelerating shell is unstable to convective Rayleigh-Taylor modes having angular scales smaller than the causality scale. It has been speculated that the convective instability may be an inherent source of turbulence in the shocked circumburst layer that leads to a strong amplification of magnetic fields over a long portion of the blast wave evolution. The linear stability analysis also indicates a rapid response of the reverse shock to distortions at the contact, suggesting that the instability can affect the emission from the shocked ejecta in the early post-prompt phase of GRBs, and may be the reason for the apparent lack of optical flashes.

4. Multi-messenger probes

Multi-messenger emissions carry important information that is not accessible to electromagnetic radiation, primarily because the innermost regions of the relativistic outflows and their engines are opaque to electromagnetic radiation. Recent and
future experiments, specifically LIGO and EGO, cubic km neutrino telescopes, and the Auger UHECR experiment will hopefully advance our understanding further. Detection of gravitational waves from GRBs for instance can be used to probe the innermost region of accreting Kerr holes. Detection of VHE neutrinos will pin down the composition of the jets, and will provide more stringent constraints on particle acceleration. Optimistic estimates suggest that blazars, microquasars, and GRBs may all be detectable by cubic km neutrino telescopes under optimal conditions. The association of UHECRs with any astrophysical source has already interesting implications, as discussed below.

The origin of UHECRs (those above the ankle) is still a mystery. It is widely believed that the sources are extragalactic, though they have not yet been identified. The confirmation of a GZK feature in the data strongly supports a bottom-up scenario, as otherwise such a scale would appear as a peculiar coincidence. There is some evidence for a weak anisotropy in the arrival directions of UHECR events that suggests a correlation of the UHECRs sources with the large-scale structure in the local Universe. A general constraint on UHECRs sources can be derived from the requirement that the accelerated particles are confined to the acceleration region; specifically that the escape time \( t_{\text{esc}} = r/c \Gamma \) is longer than the acceleration time \( t_{\text{acc}} \approx r_L(\epsilon)/c \), where \( r_L(\epsilon) \) is the Larmor radius of a particle having energy \( \epsilon \). This gives a relation between the source size and the strength of magnetic field that depends to some extent on the composition of UHECRs. Under the assumption that the UHECRs are accelerated in a relativistic magnetized outflow this also implies a minimum outflow power

\[
L_j > 10^{46} \Gamma^2 \left( \frac{\epsilon}{10^{20} \text{eV}} \right)^2 \text{erg s}^{-1}.
\]

From it is seen that AGNs with \( m_{\text{BH}} \gtrsim 10^9 \), \( \dot{m} \sim 1 \) and GRBs can account for the required power. Strongly magnetized \((B > 10^{14} \text{ G})\) neutron stars are also potential candidates. The lack of bright AGNs within the GZK sphere implies the existence of dark blazars if the UHECRs indeed originate from such objects. A total radiative efficiency of the order of that inferred in M87 is sufficiently small to satisfy observational constraints.

The condition should not necessarily apply in cases where the UHECRs are accelerated in regions that violate ideal MHD, e.g., starved black hole magnetospheres in dormant AGNs or boundary shear layers in subrelativistic jets. The former scenario predicts a deletable, magnetospheric TeV emission owing to curvature losses. With the new generation ICTA it should be possible to test this hypothesis with a high statistical significance.

Acknowledgments
Support by an ISF grant for the Israeli Center for High Energy Astrophysics is acknowledged.
References

1. I. Contopoulos, et al. Astrophys. J., 702 (2009) L148
2. W.-X. Chen and A. M. Beloborodov, Astrophys. J., 657 (2007) 383
3. A. Levinson and D. Eichler, Astrophys. J., 594 (2003) L19
4. J. N. Bahcall and P. Meszaros, Phys. Rev. Lett., 85 (2000) 1362
5. A. M. Beloborodov, arXiv:0907.0732 (2009)
6. Y. Barzilay and A. Levinson, New Astron., 13 (2008) 386
7. B. D. Metzger, T. A. Thompson and E. Quataert, Astrophys. J., 676 (2008) 1130
8. L. Yan-Rong, et al. Astrophys. J., 699 (2009) 513
9. R. D. Blandford and A. Levinson, Astrophys. J., 441 (1995) 79
10. J. Granot, et al. arXiv:0905.2206 (2009)
11. A. Levinson, Int. J. Mod. Phys. A, 21 (2006) 6015
12. S. Komissarov, et al. Mon. Not. Roy. Astron. Soc., 394 (2009) 1182
13. Y. Lyubarsky, arXiv:0909.4819 (2009)
14. A. Tchekhovskoy, R. Narayan and J. C. McKinney, arXiv:0909.0011 (2009)
15. A. Levinson and O. Bromberg, Phys. Rev. Lett., 100 (2008) 131101
16. B. Katz, R. Budnik and E. Waxman arXiv:0902.4708 (2009)
17. O. Bromberg and A. Levinson, in preparation
18. V. Bosch-Ramon and D. Khangulyan, Int. J. Mod. Phys. D, 18 (2009) 347
19. A. A. Abdo, et al. Astrophys. J., 706 (2009) 56
20. A. A. Abdo, et al. Astrophys. J., 701 (2009) 123
21. P. Meszaros and E. Waxman, Phys. Rev. Lett., 87 (2001) 171102
22. A. Levinson and D. Eichler Astrophys. J., 418 (1993) 386
23. D. Giannios, P. Mimica and M. A. Aloy, Astron. Astrophys., 478 (2008) 747
24. A. Levinson, Astrophys. J., 705 (2009) 213
25. M. H. Van Putten, et al. Phys. Rev. D, 69 (2004) 044007
26. A. Atoyan and C. D. Dermer Phys. Rev. Lett., 87 (2001) 221102
27. A. Levinson and E. Waxman Phys. Rev. Lett., 87 (2001) 171101
28. C. Distefano, et al. Astrophys. J., 575 (2002) 378
29. H. R. Christiansen, M. Orellana and G. E. Romero, Phys. Rev. D, 73 (2006) 063012
30. E. Waxman and J. Bachall Phys. Rev. Lett., 78 (1997) 2292
31. The Pierre Auger Collaboration, et al. 2008, Astropart. Phys., 29, 188
32. T. Kashit and E. Waxman, J. Cosmology Astropart. Phys., 5, (2008) 6
33. E. Boldt and P. Gosh, Mon. Not. Roy. Astron. Soc., 307 (1999) 491
34. A. Levinson, Phys. Rev. Lett., 85, (2000) 912
35. F. Rieger and F. Aharonian, Astron. Astrophys., 506 (2009) L41