Workshop Summary

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Abstract. I present a general overview of the results discussed during the Cracow 1997 workshop on “Relativistic Jets in AGNs”. My emphasis will be on showing the significant progress made in several areas over the last few years, pointing out what I feel are some of the more important issues still facing us today, and suggesting where progress is likely to be made in the near future.

1. Introduction

This workshop was unusual in that it brought together participants with a wide variety of expertise, from observational radio astronomy to numerical modeling of acceleration processes in plasmas. The rapid observational progress made in studying relativistic jets and the richness of the jet phenomenon in general were evident in the impressive range of jet emission energies, spanning over 15 decades from Gigahertz radio frequencies to TeV gamma-ray energies, and jet length scales, from astronomical units to megaparsecs, discussed by the participants.

As a convenient reference point in time to highlight the progress we have made, I choose the end of the 1980s when I was shipped off by my graduate thesis adviser to take notes for him at a VLBI workshop in Socorro, New Mexico. With the exception of the enigmatic object SS 433 in our Galaxy, relativistic jets seemed to me confined largely to galaxies belonging to the 3C radio catalog, in particular 3C 273, 3C 279, and 3C 345 which were the subjects of numerous talks. At the time, VLBI “experiments” to detect fringes from sources were difficult undertakings involving major international collaborations, hence the tendency to look at the same sources. Plot after plot was shown of highly distorted “blobs”, many of which, despite the distortions, could be seen to move in roughly straight lines on the sky with apparent velocities exceeding the speed of light. Usually, but not always, the motion of the VLBI blobs was aligned with the orientation of the jet on VLA scales. When it was not, this was tentatively interpreted as an indication that the jet was somehow being bent. The
superluminal motion of the blobs, together with the lack of two-sided jets on VLBI scales, and the fact that the fainter of the two VLBI-scale radio jets typically showed less polarization than the brighter one (presumably because the faint one was oriented away from us and was seen through more depolarizing matter) were taken as strong arguments that we were seeing Doppler boosted emission from relativistically moving fluid in the jets. Although the details were still being debated at that meeting, the “unified model”, where most differences in radio morphology and jet power could be explained away as simply a function of Doppler boosting and the observer’s viewing angle, seemed generally accepted. The inner jets in powerful Fanaroff-Riley II (FRII) sources seemed to have typical bulk Lorentz factors $\sim 10$, while those in systematically less powerful Fanaroff-Riley I (FRI) sources had lower Lorentz factors $\sim 4$. This conclusion, however, was still based on superluminal motion studies of a rather small sample of objects. This unification scheme, of course, applied only to the “radio loud” quasars containing jets. Most Active Galactic Nuclei (AGN), about 90%, were instead “radio quiet” down the milli-Jansky level and did not show any jets.

The main radiation mechanism responsible for the observed jet emission was thought to be synchrotron self-Compton (SSC) emission from energetic electrons or electron-positron pairs. The Compton component of the emission seemed to be more or less of a nuisance and upper limits on the Compton emission (at X-ray) energies were mainly useful for putting lower limits on the bulk jet Lorentz factor (so that the Compton catastrophe, where all the SSC power ends up in the Compton component, could be avoided). The emission from jets was thus a phenomenon limited mainly to the radio and optical, with a small component in X-rays. The COS-B satellite had detected GeV gamma-ray emission from one jet source (3C273), but it was weak and not thought to be associated with the jet. Balloon flights had detected strong MeV emission in several other AGN that did not contain jets, e.g., NGC 4151. The GeV emission seen in 3C273 was probably just the high-energy tail of a similar MeV emission component. Indeed, at one point it was speculated that all AGN might have gamma-ray emission at the level of the 3C273, and that this could explain the gamma-ray background detected by Sas-II. One exception to the view that jets should produce little high-energy emission was the of paper Melia & Königl (1989) where jets were presumed to start out with very high bulk Lorentz factors ($>10^3$) and radiatively decelerate to their observed terminal Lorentz factors $\sim 10$. At that workshop, Arno Witzel also gave one of his first talks in which he swore he had observed the radio emission from one source vary $\sim 20\%$ on a few hour timescales. If intrinsic to the source, this intraday variability (IDV) implied a very high brightness temperature incompatible with the standard SSC models and jet bulk Lorentz factors. People were interested, but no one really knew what to make of this observation if it proved to be correct. I also noticed one poster paper discussing a strange new class of sources (“compact doubles”) where VLBI observations of their centers showed two or three stationary emission components which didn’t fit into the standard relativistic jet picture. Overall, I came away from that meeting already thinking that relativistic jets were rather nifty, amazing objects. Little did I know what was to come, however. In the sections below, I will try to give an overview of the exciting new results reported and reviewed during the present workshop as well as of some of
the still-outstanding problems we need to address. I conclude by speculating on where some of the advances in the next few years may come from. I apologize in advance for anyone’s work I may have misrepresented or left out; the errors and omissions are mine.

2. Recent progress in understanding jets

2.1. Observations

2.1.1. VLBI (parsec-scale) radio jets in AGN

Our VLBI observing capabilities have improved markedly over the last ten years. The maximum spatial resolution available has increased due to our ability to observe at higher frequencies and use longer baselines involving space satellites. The arrival of the VLBA now lets us make maps with unprecedented dynamic range on a fairly routine basis, and allows us to contemplate monitoring many more sources than was possible before. One example of interest is the observation of M87 by Junor & Biretta (1995) which shows the jet in M87 exists and is apparently well-collimated down to distances \( \sim 100 \) Schwarzchild radii (\( \sim 10^{16} \) cm) from the central black hole. Another is the apparent detection of parsec scale circular polarization at the 0.5\% level in 3C84 and 3C279 (Homan et al. 1997). If confirmed, circular polarization will be an important diagnostic for the source geometry and magnetic field structure and the energy distribution of the emitting electrons (e.g., Bjornsson 1990). One final one is the report by Gabuzda (this proceedings) of the detection of rapid (intraday) variability in VLBI monitoring campaign of the BL Lac PKS 2155 where the polarization varied in one emission component but not another, which should have implications for our understanding of the intraday variability phenomenon. My impression, though, is that the benefits of these new capabilities are just starting to be realized and more is to come.

Overall, the general picture emerging at that Socorro workshop seems to have withstood more detailed scrutiny. The inferred magnetic fields in the VLBI jets of powerful quasars still seem preferentially aligned parallel to the jet axis, while in BL Lacs, they are aligned perpendicular to the jet axis. The current interpretation is that in the BL Lac case we are seeing amplification of the transverse field by shock compression, and in the quasar case, we are seeing strong shearing of the field. The important point is that this systematic difference between quasars and BL Lacs seems to be real (see the review of Gabuzda here). The phenomenon of misalignment between the small-scale VLBI and larger scale VLA jets also seems relatively common and is interpreted as evidence of jet bending, perhaps due to interaction with a surrounding medium. There is more evidence (e.g., Zensus et al. 1995) that the jet on the VLBI scales can have a complicated structure, perhaps due to bending or precession or simply due to a complicated shock structure in the jet (e.g., see contributions by Martí and Gomez). Particularly in the object 3C345, the radio-emitting blobs appear to be shot out initially in different directions and then converge to move on the same trajectory in the sky. Detailed studies of the blob motions in other objects
sometimes show deviations from straight-line motion, with blobs accelerating and decelerating. The poster I had noticed at Socorro on “compact doubles” now seems to have mushroomed into a full-blown field of study of Gigahertz-Peaked Sources (GPS) and Compact Symmetric Objects (CSO) (see Bicknell here and Bicknell et al. 1997 for an overview). These sources look like classical double radio-lobed sources except that they are much smaller in scale (0.1 - 1kpc). The current thinking is that we are seeing the working surfaces of two-sided jets as they ram into a dense interstellar medium, and that the observed radio spectrum at low frequencies is attenuated by free-free absorption and perhaps induced Compton scattering in the surrounding gas. Even on small scales, it thus appears that jet morphology can be significantly influenced by the environment.

2.1.2. Interactions of jets with ambient matter on larger scales

With HST we can now resolve optical features down to similar scales as the VLA (~ kpc scales), and we can begin to make detailed radio-optical comparisons. In his presentation, Falcke (this proceedings) showed HST pictures of an AGN Narrow Line Region (NLR) where much of the high excitation emission occurred on the edges of the radio jet feature — just what one might expect for a jet running into matter, and perhaps shocking or entraining some of it. In 3C 264 (Baum et al. 1997), HST sees an optical ring at a projected radius of 300 – 400 pc from the center of the source, which is likely due to absorption by a dense circumnuclear gas disk seen nearly face-on. The corresponding Merlin (comparable to be VLA) radio map shows an initially well-collimated jet that appears to blow itself apart, losing its collimation and dimming considerably just as it reaches the outer boundary of the HST ring — again what one might expect if an initially relativistic jet ran into and entrained dense gas. In a similar vein, Bicknell (this proceedings) argues that the low power jets seen in some Seyferts are actually underluminous in radio and have much higher kinetic power than one might at first suspect. The explanation he proposes is that the jets are initially moderately relativistic and then decelerate and stop radiating once they become mass-loaded by entrainment. On even larger scales (100 kpc), we see evidence from a comparison of radio and ROSAT X-ray observations that the jet NGC 1275 interacts with the surrounding intracluster medium. Indeed, Bremer et al. (1997) argue that many of the properties of powerful, high-redshift jet radio sources can be accounted for by postulating the jets are embedded in strong cooling flows at the centers of cluster. In sum, the evidence presented at this workshop and elsewhere increasingly argues that jets do not exist in isolation and that their morphology, radiative properties, and composition can be significantly altered by their interactions with their local environments. To fully understand the jets we are seeing (e.g., to explain in part the distinction between FRI and FRII sources), I would argue that we need to fully understand the jet-external medium interaction. While this conclusion might not particularly surprise anyone, I would also argue that only recently have we begun to seriously work on this aspect of the jet problem (e.g., see Bicknell and Plewa in this proceedings).
2.1.3. Blurring the lines: radio jets in radio-quiet AGN

For me, one of the more interesting results shown in this workshop was the VLA detection by Falcke of a weak, but clearly jet-like feature in a “radio-quiet” Seyfert galaxy that according to our conventional understanding should not show jets. This appears to be a rather general result. When one looks hard enough, many AGN show evidence of jets or at least a flat spectrum radio core. A particularly striking example is the LINER (low luminosity AGN) NGC 4258, that was shown by VLBI maser observations to contain a massive central object surrounded by matter in a beautifully Keplerian, cold disk. Using more VLBI observations, Herrenstein et al. (1997) have shown the previously known radio jet on parsec-kiloparsec scales in fact extends down to 0.015 parsec (2000 Schwarzschild radii) from the central object. It seems that the sharp distinction between radio-loud and radio-quiet objects, at least as defined by the presence of relativistic radio jets, is becoming increasingly fuzzy (see Falcke, this proceedings). I discuss this more in §3.6.

2.1.4. High energy emission from relativistic jets

Perhaps the most dramatic, recent occurrence in our study of jets is the discovery that relativistic jets are (very) strong high-energy emitters. Not long after it was turned on, the EGRET gamma-ray detector on GRO saw a huge flare from a position on the sky consistent with that of the blazar 3C 279. This turned out to be the tip of a large iceberg. The detection was not a fluke, and to date, EGRET has detected almost 60 blazars extending to energies ~ 10 GeV (See the contribution by von Montigny for an observational review of blazar emission). Ironically, the radio-quiet AGN like NGC 4151 that we expected to have strong MeV gamma-ray emission turned out not to have any. (The balloon detections seem to have been due to background subtraction problems.) The only previously known gamma-ray quasar 3C273 turned out not to be typical at all of AGN, and of the gamma-ray blazars we know of today, 3C 273 turns out to be a rather feeble example.

The GeV flux levels observed from these blazars are quite impressive — too impressive in fact, corresponding to isotropic luminosities exceeding $10^{49}$ erg/sec in the brightest cases. If all quasars or even just radio loud quasars (the parent population of blazars) emitted isotropically in this way, then the sky would be glowing in GeV gamma-rays at levels ~ 10-100 above the observed ones. Also, if blazar gamma-ray emission, like the rest of AGN emission, is ultimately tied to accretion onto a black hole (presumably limited to a few times the Eddington luminosity), we infer much higher central black hole masses for blazars than we have come to expect from past AGN studies, e.g., of their optical broad line luminosity. A simple way out of these problems is to postulate that the emission we are seeing is strongly beamed. This conclusion receives strong support from the detection of strong flaring by GRO with doubling times less than a day, which without applying beaming corrections, implies a rather small size for the gamma-ray emission regions. Note that GeV gamma-rays can photon-photon pair produce on X-rays, and that blazars are also strong, variable
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X-ray emitters. If the observed X-rays and gamma-rays come from the same emission region, then we should not be seeing the GeV gamma-rays we do (they would all have pair produced) unless all the X-ray/gamma-ray emission we see is relativistically beamed by Doppler factors at least $\sim 5 - 10$ and hence our naive estimate of the emitting region’s “compactness” (opacity to GeV gamma-rays) is off by several orders of magnitude. Arguments like these and the fact that strong GeV emission is only detected from blazar AGN (radio loud quasars previously thought from radio-UV observations to have jets pointing in our direction) clinched the association of the gamma-ray emission with the same relativistics jet inferred to exist from radio observations.

The surprises did not end with the launch of GRO, however. At about the same time, the Whipple telescope (a ground-based, Cherenkov gamma-ray detector) significantly improved its sensitivity and suddenly detected the weak, nearby BL Lac source Mkn 421 at TeV (!) energies. This source and at least one other, Mkn 501, have since been confirmed by other detectors as TeV emitters. The detection of TeV emission has cosmological implications since TeV photons from high-redshift source will pair produce on the cosmic infrared background radiation before reaching us. (See the contribution of Rhode for an overview of this and of TeV observations in general.) As dramatic as the GeV variability seen by EGRET is, the TeV variability apparently can be even more dramatic. In 1996, Whipple detected several huge flares from Mkn 421 with doubling times $\sim 30$ minutes (Gaidos et al. 1996), and during this workshop, Mkn 501 was in similar flaring state, having increased its emission by a factor over 50 compared to that of the previous year. In retrospect, there probably should have been more definite predictions of strong gamma-ray emission from blazars. Radio to X-ray observations of jet synchrotron emission had already shown jets to contain very energetic electrons, and we also knew that many of the radio loud quasars showed strong optical emission originating from their accretion disks, i.e., they had very intense, unbeamed, radiation fields in their centers. If some of the energetic jet electrons resided near the central radiation field, a huge “Compton catastrophe” would result, producing copious GeV-TeV emission (Near the central black hole, Compton cooling of energetic jet electrons by the “external” unbeamed radiation dominates strongly over both synchrotron cooling in the jet magnetic field and Compton cooling on synchrotron photons produced in the jet).

In terms of understanding jet physics, the detection of gamma-ray emission is important as it lets us measure exactly how much radiative dissipation is occuring in the jet (Before GRO, theorists could invoke arbitrary dissipation as long it occurred at unobservable gamma-ray energies. With GeV measurements of individual sources and of the diffuse gamma-ray background, that window of escape is now closed. Unless most of the jet power is in a component that does not couple electromagnetically like neutrinos, which is unlikely, we know the bolometric luminosities of jets to within factors of a few. Note that one cannot hide power at higher photon energies as it will cascade down to GeV energies and overproduce the background there, e.g., Coppi & Aharonian 1997.). As in the case of pulsars, the radio emission we have so laboriously studied in AGN jets turns out to be a minor, energetically irrelevant, component of the total jet emission. In pulsars, the observed gamma-ray
luminosity can often be $\sim 30\%$ of the total spin-down luminosity available and often dwarfs the radio luminosity by two orders of magnitude. In blazars, the gamma-ray power typically dominates the radio-optical synchrotron power by factors $\sim 10$ and also appears to represent a significant fraction of the total jet kinetic power. Interestingly, the gamma-ray power, while large, does not appear to significantly exceed the jet kinetic power inferred from studying the radio lobes at the ends of the jets — an important constraint on radiative deceleration models for jets.

To make progress in understanding where and how jets dissipate radiatively, we will need simultaneous, multi-wavelength observations of blazar variability from radio to TeV energies (Except in radio where we can do VLBI, we have little hope of spatially resolving blazar X-ray/gamma-ray emission in the near future.). The results of recent monitoring campaigns were discussed in several talks at the workshop see in particular those of Maraschi and Takahashi). The current results are far from being conclusive, but a general pattern seems to be emerging. Whenever a blazar is found in a high gamma-ray state, the emission from $\sim$ optical to X-ray is also in a high state, i.e., the emission at high and low energies seems to be strongly correlated. When a sharp gamma-ray flare occurs, optical, UV, and X-ray flares are also seen. Particularly in the BL Lac objects Mkn 421 and Mkn 501, the X-ray and gamma-ray (TeV) emission seem very tightly correlated, with little lag. Below X-ray energies, the amplitude of the flaring seems generally to decrease, perhaps due to dilution from a non-varying component, and my impression is that low-energy flaring tends to lag the high-energy flaring (although I note that in one case, an optical flare may have preceded a gamma-ray flare — i.e., we need many more observations).

Determining which parts of the spectrum lag or lead other parts of the spectrum is particularly crucial to understanding the dynamics of the particles responsible for the emission and disentangling various emission components. Right now, it is not completely clear what we should expect, e.g., in blazars where Compton upscattering of photons external to the jet is important, a flare can be caused by an increase in either the number of target photons (optical leads gamma-rays) or the number of energetic particles (gamma-rays lead optical). As an example of where we may already have made significant progress, Takahashi (this proceedings) presented a set of ASCA observations of Mkn 421 that show the X-ray emission at $\sim 1$ keV lagged that at $\sim 10$ keV during during a strong TeV flare. Also, when the X-ray spectral index was plotted versus intensity at a fixed observing energy, a characteristic “hysteresis” curve appeared (see Takahashi). Both the lag and hysteresis curve are exactly what one expects if the X-ray emission is synchrotron and one is seeing the spectral response to a rapid injection of very energetic electrons which then cool slowly to lower energies (e.g., see Kirk, this proceedings). This, together with the tight X-ray/TeV correlation, lends strong support to the picture that, in BL Lacs at least, we are seeing SSC emission (with the synchrotron component dominating at X-ray energies and below, and the Compton component dominating at gamma-ray energies). Although data like this is highly suggestive, I would like to stress that it is still relatively sparse and the conclusions far from certain.

The rapidly variable emission I have been discussing probably comes from the inner, sub-parsec regions of the jet. However, the outer parts of the jet almost certainly
also emit at high energies, at least in X-rays. On the parsec scale, Unwin et al. (1997) have shown that in 3C 345, the overall level of X-ray emission correlates with the emergence of radio VLBI features. Worral (this proceedings) showed evidence from ROSAT observations of centrally obscured jets that there is extended jet emission, perhaps out to kiloparsec scales, and Tashiro (this proceedings) presented positive ASCA detections of X-ray emission from jet radio lobes, probably from Compton upscattering of cosmic microwave background photons by the energetic electrons in the lobes. If one is making blazar observations without good spatial resolution and the source is not clearly in a very strong flare state, any interpretation should take into account the possible contributions from the larger scale jet.

2.1.5. The discovery of microquasars

As a testament to the ubiquity of the jet phenomenon, the last few years have also seen the discovery of jets from black holes right in our own Galaxy (see the overview by Ziolkowski, this proceedings). Although the masses of these black holes are eight orders of magnitude smaller than those of powerful AGN, the Galactic jets appear rather similar to the AGN ones, and in particular, show superluminal motion.

2.2. Phenomenology

2.2.1. General radio-loud quasar unification schemes

The last ten years have seen significant progress in firming up the links between the various members of the zoo of radio-loud AGN. The apparently diverse members of this zoo go by such names as X-ray Selected BL Lacs, Radio Selected BL Lacs, FR-I/II radio galaxies, High Polarization Quasars, Optically Violent Variables, Flat Spectrum Radio Quasars, Steep Spectrum Radio Quasars, Gigahertz-peaked Sources, Compact Steep Spectrum sources — to name a few. The first crucial link between all these objects is that they all appear to contain jets. The second is that all their jets probably start out with moderately to very relativistic bulk velocities, i.e., the emission from the inner jet will be Doppler boosted and anisotropic as a result. Depending on the orientation of the jet relative to the observer, one will see very different spectra. Shastri (this proceedings) showed an example of this, where the ROSAT spectral index of radio quasars/galaxies varies systematically with the core dominance parameter \( R \) (an orientation measure if jet emission is beamed). If the jet points towards us, the boosted jet emission dominates and one sees an often featureless, rapidly variable continuum. If the jet points away from us, one sees only the more or less isotropic emission from the underlying black hole accretion disk (e.g., the broad emission lines seen in radio-quiet AGN). As summarized by Urry in her talk (see the review of Urry & Padovani 1995 for details), we have now have accumulated a fair body of evidence that a gross unification scheme, based on viewing angle and characteristic jet bulk Lorentz factors as the main parameters, actually works. The remaining major differences, e.g., between the morphologies of FR-I and FR-II galaxies, right now seem probably due to differences in the initial jet power and the interaction of the jet with ambient matter (FR-I jets are
weak compared to FR-II jets and may entrain considerable matter; Gigahertz-peaked sources generically show high rotation measures and depolarization, i.e., signatures consistent with their being surrounded by dense gas.

2.2.2. The “strawman” (SS+E)C model and blazar unification schemes

At this workshop, a clear “strawman” model for explaining the variety of blazar spectra we see (see the contributions of Ghisellini, Fossati, Kubo, Takahashi, and Takahara). Namely, that all blazar spectra can be explained by a one-zone, homogeneous “(SS+E)C” model. In this model, energetic electrons located somewhere near the central black hole emit synchrotron photons, and these jet photons together with some number of external photons are Compton upscattered by the electrons to high energies. The only parameters for this model are the source region radius, the bulk jet Lorentz factor, the energy of the external radiation field in the source frame (\(U_{\text{rad}}\)), the energy density of the magnetic field in the source frame (\(U_B\)), the minimum and maximum “injection” energies of accelerated electrons/pairs, the power law index of the electron/pair energy injection function, and the total power supplied to the injected pairs. I do not think this model can be right in detail, e.g., cascading may be important in some sources and the emission we see is very likely the superposition of several components and/or electron acceleration events. However, as a first order phenomenological model, it seems to work remarkably well, especially for spectra during strong flares where one localized emission component may well dominate. In a burst of enthusiasm, Ghisellini (this proceedings) has fit all the broad-band blazar spectra he could find and has come up with a very interesting correlation hinted at by other participants: the energy of the electrons responsible for the emission at the peaks of the synchrotron and Compton components seems to systematically decrease as the sum of the magnetic and external radiation energy density (\(U_B + U_{\text{rad}}\)) in the jet frame increases. For some reason, perhaps a balance between acceleration and radiative cooling timescales, powerful sources (which presumably have stronger external radiation fields and jet magnetic field) do not accelerate electrons to as high an energy as weak sources. This scenario is appealing as it explains the puzzling differences between X-Ray Selected BL Lacs and Radio Selected BL Lacs. The Radio Selected BL Lacs are known to be more luminous on average, hence their synchrotron emission should peak at lower energies (in the optical-UV), and they would not be picked up as often in X-ray surveys. Also the scenario is consistent with the recent finding of Padovani et al. (1997) that the distribution of X-ray spectral indices for Flat Spectrum Radio Quasars (powerful objects, several of which have been detected by EGRET at GeV energies) is consistent with that of LBLs (“Low-energy cut-off BL Lacs”, in their terminology) and with the Compton component dominating the X-ray emission seen in both these classes of objects. In this unified picture, then, the spectra of all blazars are essentially the same except that they are shifted up and down in frequency depending, roughly, on their luminosities (and probably details of exactly where the particle acceleration occurs). The complete picture may be more complicated, however, as the ratio of the luminosities in the Compton and synchrotron emission components seems also to depend on the total source luminosity; in
BL Lac objects, the ratio never reaches values as high as those seen in quasars. This may reflect the fact that accretion disks in BL Lacs are systematically underluminous compared to quasar ones, i.e., there are relatively fewer external photons in BL Lacs.

2.3. Theory

The preceding scenarios are very elegant, but they provide no answers as to why, for example, the “(SS+E)C” model should have the physical parameters it does. For example, what determines the energy distribution of the relativistic electrons in jets? Unfortunately, as noted by Li et al. (this proceedings), “The need for understanding particle acceleration is stressed by every high energy photon we observe.” As a theorist, I am slightly ashamed to say we have not kept up with observations on questions like this. The theoretical questions posed ten years ago and the answers tentatively proposed for them are still largely the same: What creates and collimates the jets in the first place? Does the black hole play a role (e.g., via the Blandford-Znajek effect or the coupling of the black hole spin to the accretion disk) other than providing a strong gravitational potential? How are particles accelerated? What roles if any do shocks, MHD wave turbulence, and large-scale “parallel” electric fields play? (For discussions of these last points, see, respectively, the contributions by Kirk, Ostrowski, Li, and Colgate.) If the gamma-ray emission region, the place where the bulk of the internal jet dissipation seems to occur, always lies in some preferred region of the jet, why? Is it the region where a Poynting flux-dominated jet is transformed into a particle-dominated one? (See the discussion by Levinson for more.) Because the theoretical issues involved are rather technical, I will not discuss them further. Rather, I will try to conclude on a more positive tone by noting that there was evidence for significant theoretical progress at this workshop. Relative to ten years ago, the theory of shock acceleration is in much more robust shape. Also, we have developed much more powerful radiative transfer codes and models (e.g., inhomogeneous, multi-zone ones) that can be brought to bear once the observations tell us what direction to move in. Finally, of particular relevance to radio observations, were the impressive jet simulations presented by Martí and Plewa. The three-dimensional, high resolution simulations of Martí were essentially unthinkable even five years ago. Today, instead, we are beginning to carry out fully relativistic, three-dimensional, MHD simulations. Although the connection between the jet fluid properties and particle acceleration (and radiation) is still lacking in these simulations, one can now begin to make more educated guesses as to what a real jet should look like. The simulated VLBI observations shown by Gomez were enlightening as they graphically illustrated the complicated emission patterns (e.g., see Lind & Blandford 1985) that can arise in a realistic fluid flow, where shocks and fluid elements temporarily move in different directions with different velocities.

3. Some new and old unresolved problems

As Meg Urry noted in her talk, “The greater our sphere of knowledge, the larger its surface of contact with our ignorance.” Below, I summarize some of the unresolved
issues brought up during the discussion section of the summary talk, plus a few others I feel are important.

3.1. How variable is blazar emission?

As discussed by Stefan Wagner, if one thing is clear about blazars, it is that their emission is extremely variable at practically all wavelengths. At radio frequencies, we see intraday variability in intensity and polarization on the order of $\sim 20\%$. At GeV energies, EGRET has also seen intraday variability, with the source PKS 1622−297 showing an increase of a factor $\sim 4$ in less than 7 hours (Mattox et al. 1997). In general, the longer EGRET has observed, the more extreme the examples of GeV variability it has found and a structure function analysis indicates that the shortest variability timescales have yet to be resolved (e.g., Wagner, this proceedings). If this were not enough, the new ground-based Cherenkov telescopes (Whipple & HEGRA) have detected variability at $\sim 1$ TeV energies on $\sim$ half-hour timescales from Mkn 421 and Mkn 501 (Gaidos et al. 1996, Bradbury et al. 1997, Catanese et al. 1997). Variability in the X-rays on comparable ($\sim$ hour) timescales has also been seen.

In light of this data, an obvious question that needs to be answered is what exactly is the shortest variability timescale as a function of energy? The answer could have a major impact on models. Already the observed variability timescales are embarrassingly short. In the case of the radio intraday variability, implied source brightness temperatures as high as $10^{16} - 18$ were were recorded in several cases, with the current record being $10^{21}$ K (Kedziora-Chudczer et al. 1996) for $\sim$ 1 hour variations seen in PKS 0405−385. These values are orders of magnitude higher than the standard inverse Compton brightness temperature limit of $10^{12}$ K. If this variability is intrinsic to the source, i.e., it is not due to propagation effects such as microlensing or interstellar scintillation, then the bulk jet Lorentz factor required to explain away the discrepancy in PKS 0405−385 is $\sim 60 - 1000$ depending on the exact emission geometry (e.g., see Begelman et al. 1994 who would argue for the value of 1000). Such values are significantly higher than the typical Lorentz factors derived, say, from superluminal motion considerations and strong beaming of this type is not compatible with the population statistics in unification schemes. In the case of PKS 0405−385, even if the variability is not completely intrinsic and is due mainly to interstellar scintillation, the apparent brightness temperatures must still exceed $10^{16}$ K (Blandford, private comm.), i.e. one still has a problem. If such apparent high brightness temperatures persist, we may be forced to consider alternate, coherent emission scenarios such as perhaps proposed in Benford (1992). Coherent emission is not without precedent in Nature, but the brightness temperatures here are so high that is not clear how the radiation can escape from the gas-filled nuclear region without significant attenuation due to stimulated processes (Coppi et al. 1993, Blandford & Levinson 1994). That being said, the observations remain. Another area where rapid fluctuations may lead to problems is the rapid ($\sim$ half-hour) X-ray and TeV flaring seen in Mkn 421/501. To explain such rapid variability and at the same time avoid catastrophic pair production of the observed TeV gamma-rays on X-rays from the jet, the flaring region must be
smaller (and closer to the central source?) than previously thought, $\sim 10^{14} - 10^{15}$ cm, and the emission must be beamed by Lorentz factors $\sim 10 - 15$ (e.g., see Gaidos et al. 1996), again higher than the typical Lorentz factors $\sim 4$ expected from the both the superluminal motion observations and beaming statistics of low-power BL Lacs like these.

On a more practical note, the details of this variability must be observationally understood and theoretically accounted for if one hopes to ever make realistic emission models for blazar jets. “Quasi-simultaneous” X-ray and TeV observations separated by order an hour are not really simultaneous if sources like Mkn 501 vary by factors of a few on half-hour timescales. A particularly critical quantity in models (see the next section) is the X-ray to gamma-ray spectral index, i.e., the amount of X-rays produced for a given level of gamma-ray emission. The fact that relatively few X-rays appear to be seen, for example, rules out models with lots of cascading, where gamma-rays from the jet pair produce before escaping the central region of the AGN. In several cases, though, my impression is that the conclusion that X-rays are “few” are based on comparisons of an X-ray flux obtained with an integration of a few hours versus a gamma-ray flux obtained with a typical integration time of two weeks. Fits to such apparently, but not really, simultaneous data can be potentially misleading. Also, in determining the “characteristic” gamma-ray emission level and energetics of blazars, we must remember that many of the EGRET gamma-ray detections probably represent extreme, perhaps atypical, flares in these sources. I would argue that we currently do not have a good handle on what the quiescent or time-averaged gamma-ray emission from blazars is (Essentially every blazar detected has had its flux drop below the EGRET detection threshold.). A potentially sobering example of this comes from the recent results of Pohl et al. (1997). In order to ascertain what contributions blazars make to the diffuse gamma-ray background at GeV energies (note that the observed background represents an integration over several years), the authors carefully coadd all the photons detected by EGRET that are consistent with having come from the direction of a strongly detected blazar. The resulting time-averaged, composite spectrum is rather soft (photon number index $> 2$) and does not look much like either the gamma-ray background spectrum nor the hard flare spectra of blazars. See the contribution of Magdziarz, Moderski, & Madejski for more discussion of some of the issues connected with gamma-ray variability.

3.2. What are jets made of and the location of the gamma-ray emission region

This general topic is one that has plagued theorists for years and received considerable discussion at this workshop. The new observational data we have available give us some important constraints, but the issue is far from resolved. As the relevant arguments are summarized well in the contributions from Celotti and Levinson, I will only repeat the highlights here. A popular explanation for observations like that of low Faraday polarization in AGN jets has been that jets are made of electron-positron pairs. However, the detection of strong gamma-ray emission from blazar jets appears to rule out scenarios where the bulk of the jet energy near the black hole is carried by
pairs. The central radiation field in an AGN is typically very intense and the radiation drag on pairs is correspondingly large. At distances less than \( \sim 10^{16} \) cm, pairs (and the jet itself if it is pair-dominated) will be decelerated to Lorentz factors of a few. Comparing the total radiative output of jets (typically dominated by their gamma-ray emission) with the kinetic jet power inferred from the radio lobes at the ends of the jets, we are finding that the radiative power of the jets can be comparable to, but not significantly greater than the kinetic power. Thus, “bulk” jet deceleration scenarios like that of Melia & Königl (1989) (where an initially very fast jet is decelerated to a terminal Lorentz factor \( \sim 10 \)) appeared to be ruled out. The inner jet cannot suffer catastrophic radiative losses, and thus if it is dominated by pairs, it must be cold and slow — often slower than the Lorentz factors \( \sim 10 \) inferred for the parsec scale jets. The jet must be slowly accelerated to its terminal Lorentz factor, in which case the jet power is initially in some other form, e.g., Poynting flux or protons which do not radiate efficiently.

Leaving aside temporarily the issue of the form in which the bulk of the jet energy resides, another issue is where and how the pairs in the jet would actually be produced. In strong sources like 3C279, if the pairs are produced near the center where the jet particle density is presumably high, they will annihilate away before propagating to the parsec scale where we can use VLBI observations to constrain the actual density of pairs. Producing pairs too far away from the sources is problematic, however, because the most efficient way to produce pairs is by photon-photon pair production, which requires an intense field of target photons. Pair production off internal jet photons is in principle possible, but the result is a compact “fireball” of the type discussed here by Thompson which could explain emission from blazars which show a strong spectral cutoff above an MeV, but not from the bulk of blazars which appear to have emission extending to GeV energies and beyond. Hence, the best site for producing pairs is near the center of the AGN, where the external radiation field is the strongest. The target photons of interest are probably UV/X-ray photons. From kinematics considerations, this means the pairs they produce must have energies above at least \( \sim 10 \) MeV. Since the pair production and Compton scattering cross-sections are of comparable magnitude, if pair production is efficient, then Compton cooling is efficient and the pairs that are produced will Compton upscatter ambient photons to X-ray energies and cool (barring some unforeseen heating mechanism for the pairs). Because of the observational constraints on the X-ray flux of blazars, the total number of pairs that can be produced is thus significantly constrained. In addition, since the pairs cool, they carry away very little of their initial energy. Moreover, if there are too many of these cooled pairs, Comptonization by the pairs (moving with the bulk Lorentz factor of the jet) should produce an observable excess of emission at soft X-ray energies, the so-called Sikora “bump” which has not been observed yet. While jets at parsec scales and beyond may contain significant numbers of pairs, because of arguments like these, it seems to me unlikely that in strong sources the bulk of the jet energy is carried by pairs at large distances (In weak FR-I/BL Lac sources, many of the preceding arguments break down and the jets could well be dominated by pairs.). However, I note that this conclusion is not the conventional one, and it faces a possibly significant problem of energetics. Takahara (this proceedings) used
his emission model to estimate the jet kinetic power in 3C279. If the observed SSC radiation comes from electrons neutralized by ambient protons instead of from pairs, the inferred jet power increases from $\sim 10^{46}$ erg/sec to $10^{48}$ erg/sec, which starts to be uncomfortably large.

The last estimate depends critically on the lowest energies of the pairs in the SSC emission region. The higher the minimum electron Lorentz factor, $\gamma_{\text{min}}$, the lower the number of electrons in the source, the lower the number of required protons and thus the lower the jet kinetic power. If electrons could somehow be maintained at high Lorentz factors ($\gamma_{\text{min}} \sim 10$), this would solve not only the possible energetics problem but also explain the low Faraday depolarization in the absence of pairs since relativistic electrons effectively behave as heavier particles and induce less Faraday rotation. Although not always noted, a minimum Lorentz factor also enters crucially into the homogeneous SSC/external Compton model for the observed spectrum. In order to match the observed spectral break at $\sim$ MeV energies, Ghisellini (this proceedings) for example assumes that energetic electrons are injected into the radiation zone with a power law energy distribution of cut off at a minimum Lorentz factor $\gamma_b \sim 100$. The steady-state Compton upscattered spectrum given such an electron injection function is a broken power law with energy spectral index $\sim 0.5$ below a few MeV and a steeper spectral index above (determined by the index of the electron injection function). The spectrum above 1 MeV can be made arbitrarily steep, giving a change $\Delta \alpha_{X-\gamma} > 0.5$, as observed in some cases (Without a minimum energy injection energy and contrived cooling rates, inefficient cooling of low energy pairs, the other mechanism proposed for MeV break, can only produce $\Delta \alpha_{X-\gamma} = 0.5$). Why such a minimum injection Lorentz factor $\sim 100$ should exist with this value is an open question. Perhaps an important clue comes from the anti-correlation shown here by Ghisellini between $\gamma_b$ and the total magnetic plus radiation energy density in the source region. I note that cascade models, e.g., those discussed by Levinson, naturally predict such a $\gamma_b$ (it is the minimum energy of the produced pairs), but I have found such models generically have problems explaining spectra like that of 3C273 where $\Delta \alpha_{X-\gamma} > 0.5$ and the X-ray spectrum is hard ($\alpha_X = 0.5$), i.e., it is not clear they apply in most objects.

Another still-open question, on which there was surprisingly little debate during this workshop (compared to others), is the exact location in the jet where energetic electrons/pairs are accelerated and the observed gamma-rays are emitted. The consensus (for strong sources) seemed to be for distances $\sim 10^{16} - 10^{17}$ cm from the central black hole. Cascade models typically can only work in this range of radii because if most of the jet dissipation (electron acceleration) occurs too close to the black hole, too much X-ray flux is produced, and if the dissipation occurs too far, there are not enough target photons to pair produce on and cascading is irrelevant. The external Comptonization models cannot work too close to the black hole because photon-photon pair production on disk photons will truncate the observed spectrum below a GeV, and they cannot work too far away (outside of the Broad Line Region) because the electron cooling times become too long and the characteristic source sizes become too large to explain the rapid flaring seen by EGRET. Purely SSC models are much less constrained since they provide their own seed photons, but the typical source region sizes (variability timescales) and magnetic fields
used in models are characteristic of the subparsec jet. Just because all these models agree roughly (to within an order of magnitude) on where the gamma-rays come from is still not definitive proof. In at least one object (Unwin et al. 1997), some of the observed X-ray flux is clearly correlated with the presence of particular VLBI “blobs” and is produced on parsec scales. The scenario of Mannheim (1993) where electron acceleration and gamma-ray emission from shocks occur on the parsec scale should not be automatically dismissed, although I feel it is more unlikely now given the very intense, very rapid gamma-ray variability that has been seen. Also in two cases (Wehrle et al. 1993, Pohl et al. 1995), strong gamma-ray flares seemed to be roughly coincident with the time a VLBI blob is extrapolated from its motion to have been emitted from the origin of the jet, i.e., the gamma-ray emission is associated with the formation of a blob, but it is over before the blob is clearly distinguishable on the VLBI scale. More attempts to correlate gamma-ray emission with the emergence of blobs observed with high-resolution VLBI would clearly be interesting. Even if we have correctly guessed the location of gamma-ray emission region, another question remains: why does so much dissipation of the jet energy occur on these size scales? I don’t currently know of a very good answer (but see the contribution of Levinson).

3.3. How many emission components do we need: is the one-zone emission model right?

Occam’s Razor suggests that we stick with the simple straw-man model for blazar emission until the data requires otherwise. With the current quality of data, the minute one allows for different source regions with different parameters, one essentially loses all predictive power (One can produce whatever one wants.). However, it would not surprise me if we are forced soon to consider more complicated models. My guess is that this may happen when we try to simultaneously fit the synchrotron and inverse Compton spectra for sources like Mkn 421 where we may have good, simultaneous, broad-band spectral data. We may find that the seed photon distribution we need to produce the observed Compton spectrum given a particular electron distribution is different from the synchrotron photon distribution generated by those electrons. If stellar jets and the microquasars are any guide, jets are highly episodic and variable phenomena. The current spectrum we observe may be the superposition of several different flares or acceleration “shots” which are in various stages of cooling down and extinguishing themselves. This possibility should not be forgotten when interpreting data. (Because of “dilution” effects, the variability amplitude at a given energy may be significantly reduced from what one naively expects.)

3.4. What are the “typical” bulk Lorentz factors for jets?

I note that during the workshop there were several instances where jet bulk Lorentz factors as high as 20 – 40 were casually tossed about when talking about emission
models (and Lorentz factors 100+ were invoked to explain away the high brightness temperatures from intraday variability). These are somewhat higher than what I was used to. I did not carry out any careful statistics, but it may be worth double-checking the agreement between emission model Doppler factors (consistent with rapid variability) and superluminal motion (VLBI-scale) Doppler factors. The structure of jets as function of distance from the central source may be more complicated and vary more than we currently suspect. The suggestion by Bicknell (these proceedings) that jets in weak sources start out as mildly relativistic and then become subrelativistic via entrainment would be one example of this that definitely deserves more investigation.

3.5. What are MeV blazars?

Focusing again on high-energy emission from relativistic jets, are there two distinct classes of gamma-ray emitting blazars: the “MeV” blazars (whose energy output peaks strongly in this energy range) and the more conventional GeV/TeV blazars? Or is there simply a continuum of blazar spectra corresponding to (in a Ghisellini-type picture) a range of minimum electron injection Lorentz factor and power law injection indices (see §3.2)? Or do MeV blazars represent a very different, compact and fireball-like source as argued by Thompson in his talk, or as argued by Sikora, are they evidence for boosted thermal emission from some hot, continuously reheated region? The unification picture is appealing, but some of the EGRET MeV blazar spectra look rather strange (showing “lines”?). The jury is still out on this question.

One further question: the radio galaxy Cen A was detected by GRO to have variable emission that definitely extended to beyond 1 MeV in some epochs (Kinzer et al. 1995). Cen A is not supposed to be a gamma-ray blazar as its jet is not pointing at us. However, is the jet responsible for this emission too? (No Seyferts have been detected at 1 MeV.)

3.6. What is the connection between jets, the accretion disk and/or the central black hole?

Although this was not addressed directly at the workshop (but see the contribution from Moderski, Sikora, & Lasota), it is still one of the key questions in our quest to understand the origin of jets. The radio loud vs. radio quiet quasar (jet vs. no jet) dichotomy has been argued as evidence for a clear difference in some intrinsic property of the central objects in these sources. A popular suggestion is that a jet is produced only when the black hole is rapidly rotating. However, as seen in this workshop, the distinction between radio loud and radio quiet is becoming muddied. Evidence for outflows that are at least mildly relativistic (in the initial stages) seems to showing up in most AGN when one looks hard enough. In the Galactic camp, we also have both confirmed black hole (GRO J1655) and neutron star (Cir X-1) binary systems that show jets. The only thing in common between these systems is presumably the deep gravitational potential well and the presence of an accretion
disk. Perhaps a jet is mainly a phenomenon related to the accretion disk, and in the case of AGN, the distinction between strong and weak radio jet sources has more to do with the environmental conditions in the central region of the AGN (e.g., the density of ambient gas) rather than black hole? (For example if a starburst is going on in the center, the central gas density may be very high and entrainment will “kill off” the jet.) Motivated by detailed numerical simulations, Meier et al. (1997) have also proposed a very interesting picture where all disks generate outflows with a kinetic luminosity that grows as the characteristic strength of the magnetic field in the disk grows (with the strength of the field in the disk presumably scaling with the mass of the central object). The outflow is mildly relativistic until the disk field strength exceeds a critical “switch” and the flow then becomes strong relativistic. This could explain the apparent continuity in FR I/FR II radio power, but the relatively sharp distinction in FR I/FR II radio morphology. On the other hand, based on the relative intensities of the synchrotron continuum and broad emission lines, BL Lac/FR I galaxies have disks that appear to be subluminous compared to those in radio loud galaxies. To power the jet, we may require an additional source of energy, such as could be provided by the central black hole via the Blandford-Znajek mechanism (In principle, then, when the fueling of the black hole has almost completely stopped, we could still see a jet.).

4. Future prospects

As breathtaking as it has been, the rush of observational information on jets is likely to continue. On the radio front, we have only just begun to exploit the capabilities of the VLBA. For the first time we may able to discern ambient gas clouds illuminated by the high brightness temperature emission of a jet and thus learn more about the environment through which the jet propagates. Space based VLBI, such as is already being carried out using the VSOP satellite, will further increase the spatial resolution available to us and will either resolve the cores of radio-loud AGN or raise the lower limits on the brightness temperature of cores from the already uncomfortably high values of $\sim 10^{12} K$ observed in some cases (At such high brightness temperatures, induced Compton and Raman scattering effects may become important, e.g., see Coppi, Blandford & Rees 1993.). Unlike the IDV brightness temperature estimates based on variability, these are based on direct spatial constraints and are much more robust. In general, the VLBA together with an upgraded European VLBI network will allow for much more frequent monitoring of many more sources than has been possible before. Multi-frequency polarization observations (including perhaps circular polarization) should become relatively routine. Gabuzda has already presented an example here where monitoring of PKS 2155 found a 5 hr (intraday) variation in the polarization of one VLBI component but no variations in another. Such behavior is not entirely unexpected as the result of interstellar scintillation, but if confirmed in other sources, it may lead to some interesting constraints on the interstellar scintillation explanation for IDV.
At optical wavelengths, continued use of HST coupled with high resolution observations of the VLA will provide us more detailed examples of jet-ISM interactions, such as we have begun to see at this conference. Combined high spatial resolution optical and radio observations will also allow us to watch how a synchrotron-emitting population of electrons ages and provides constraints on the particle acceleration mechanisms, e.g., as was done for the shocks in the jet of M87 (Stiavelli et al., 1997).

In addition, several large CCD mosaic instruments will be coming on-line in the next few years (e.g., the Sloan Digital Sky Survey, Megacam at CFHT). These will allow deep quasar surveys covering much of the sky. Over the next few years, the number of optically confirmed quasars, including those with jets, should increase at all redshifts ($z < 5$) by well over an order of magnitude. The current world sample of quasars is of order 10,000; the 2DF survey in Australia has already obtained a list of 25,000 good UV-selected candidates and will take spectra of all them in the next few years. The optical surveys can be cross-correlated with radio and X-ray surveys, producing a very large, multi-wavelength sample which will enable us to test, for example, unification schemes and orientation effects in even more detail.

In the X-ray range, the arrival of AXAF with its 0.5" spatial resolution and excellent spectral resolution will allow us to map in more detail X-ray emission from the outer regions of the jet (e.g., see Diana Worrall in this proceedings) or study how a jet shocks and interacts with an intracluster medium (e.g., as in the case of NGC 1275, Fabian et al. 1994). Of interest to those modeling high energy emission from jets, the arrival of satellites with broad-band ($\sim 1keV - 100 keV$) capabilities and good sensitivity like SAX and XTE will allow us to simultaneously monitor the time evolution of the synchrotron and Compton emission components (assuming the SSC picture is correct). In one shot, we can monitor the evolution of the emitting particle distribution at the highest and the lowest energies (the high energy electrons produce the typically $\sim$ keV synchrotron emission and the low energy electrons are responsible for the Compton upscattered emission observe at higher photon energies). Such information will be crucial for testing inhomogeneous vs. homogeneous jet emission models and detailed acceleration scenarios. XTE will be particularly useful because of its large collecting area. In the case of Mkn 421, TeV flares were observed to occur on timescales as short as half an hour (Gaidos et al. 1994). With Mkn 421 at its typical emission level, XTE should be able to probe variability down to the level of a few minutes. The expectation is that we will finally reach the shortest timescales on which blazars vary and effects due to finite source size and finite acceleration time become apparent (Perhaps we will see the “reverse hysteresis” discussed by Kirk in his contribution.). If we do not see evidence for a lower limit on variability timescales, then the corresponding limits on the size of the emitting region and the jet Doppler beaming factors become even more interesting. (Already, in Mkn 421 beaming factors $\delta \sim 15$ are talked about, which is considerably larger than typical BL Lac beaming factor $\sim 4$ obtained from unification scheme and superluminal motion studies.) Instruments like XTE and SAX also typically include all-sky monitors designed to pick up transient events, such as the flare of a low mass X-ray binary system in our galaxy. The number of known galactic black hole binary systems, including “microquasars”, should thus increase significantly over the next few years.
In the range 100 keV - few MeV, which has traditionally been difficult to observe, significant improvements in sensitivity compared to GRO should come from the planned launches of the Integral and Astro-E satellites (Current data in this range comes mainly from the Comptel instrument on GRO, which has a rather low sensitivity.). This is the energy range where the high-energy spectra of blazars show a break, resulting perhaps from the inefficient cooling or escape of electrons/pairs below a certain energy. In some cases, the “MeV blazars”, the break actually appears to be very sharp and the energy output of the blazar peaks in this energy range. The explanation for this break is not at all clear. As discussed by Sikora and Thompson here, understanding it has important implications for the blazar emission model as a whole.

Finally in the range of 10 MeV and above, we will have a temporary dearth of data now that the high-energy EGRET instrument on GRO has come to the end of its useful life and a replacement for EGRET, perhaps GLAST, is not likely to be launched for at least several (ten) years. This deficit in energy coverage, however, is being rapidly filled in by ground-based Cherenkov detectors. The low-energy threshold of these detectors is currently \( \sim 200 \) GeV, but work is already underway or planned (e.g. the MAGIC, CELESTE, STACEE) to lower this threshold to \( \sim 50 \) GeV. The currently existing Cherenkov detectors (Whipple, HEGRA, CAT, CANGAROO), however, have already proven themselves to be extremely useful for nearby blazars like Mkn 421 and Mkn 501 (e.g., see the papers on the recent Mkn 501 flare by Bradbury et al. 1997, and Catanese et al. 1997). Perhaps the key attribute of these detectors to bear in mind is their very large collecting area, already at least \( 10^4 \) times that of EGRET. Since these detectors are located on the ground, they are not subject to the stringent size and weight limitations that constrain space-based detectors (The sensitivity of a Cherenkov detector can in principle be increased arbitrarily by putting together an ever larger array of Cherenkov mirrors.). The result is that while EGRET can resolve flares down to timescales of several hours (for the very brightest events), current Cherenkov detectors can probe variability on timescales of 15-30 minutes. Given the extreme variability of blazars, such timing capability is crucial and complements well the capabilities of an instrument like XTE. Detailed correlation studies of X-ray and TeV variability will be among the most important in constraining and testing the SSC model for the emission of nearby, weak blazars like Mkn 421. (In fact, successful studies of this type have already been carried using ASCA and Whipple, e.g., see the contribution of Takahashi et al.) With stereoscopic imaging techniques, Cherenkov energy resolutions \( \sim 25\% \) can be achieved at \( \sim \) TeV energies. Thus it will be possible to carry out detailed spectral, not just intensity, comparisons.

From my perspective, the next few years should prove rather exciting. I look forward to the next meeting in Kraków...

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