Frontiers of Astrophysics - Workshop summary[1]

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We summarize recent results presented in the astrophysics session during a conference on "Frontiers of Contemporary Physics". We will discuss three main fields (High-Energy Astrophysics, Relativistic Astrophysics, and Cosmology), where Astrophysicists are pushing the limits of our knowledge of the physics of the universe to new frontiers. Since the highlights of early 1997 were the first detection of a redshift and the optical and X-ray afterglows of gamma-ray bursts, as well as the first well-documented flares of TeV-Blazars across a large fraction of the electromagnetic spectrum, we will concentrate on these topics. Other topics covered are black holes and relativistic jets, high-energy cosmic rays, ν-Astronomy, extragalactic magnetic fields, and cosmological models.

1. INTRODUCTION

Astrophysics has become one of the most rapidly evolving disciplines in physics over the last two decades. An aggressive expansion, mainly driven by new technology, has pushed the limits for the observer further in photon energy, sensitivity, and spatial resolution and new sub-disciplines are being added to astronomy and astrophysics at a breathtaking speed. Young fields like x- and γ-ray astronomy already play an integral role in the scientific community, while TeV- and Neutrino-astronomy are knocking at the door.

Though even the established astronomical sub-disciplines have legions of their own frontiers, we will here concentrate on the very forefront of astronomy where astronomy is pushing the very frontiers of physics itself. Three of those fields were selected for this workshop:

a) High-Energy Astrophysics, where we can study photons and particles from cosmic accelerators with energies way above what can be produced in laboratory on Earth—unfortunately, we even do not understand those cosmic accelerators yet.

b) Relativistic Astrophysics, where we can study General Relativity in the strong limit never reached in our solar system. Black Holes are one example, which most astronomers consider already well established while many physicists wait for the final proof—and there is hope.

c) Cosmology, the most fundamental, yet sometimes also most fantastic part of physics, where astronomy provides the basic data and sets the framework for any cosmological model.

Despite the importance of all those questions, a small workshop like this is of course always dominated by the personal interests of the scientists present and the and the most recent discoveries. The spring of 1997 was especially marked by two major new observational developments:

First, the afterglow of the enigmatic Gamma Ray Bursts (GRBs) was observed in X-rays, the optical and also in the radio. One also obtained the first lower limit for the redshift of a GRB, demonstrating fairly convincingly, that GRBs are cosmological.

Second, Blazars, this fascinating subclass of quasars, were observed to tens of TeV photon energy (marking the advent of TeV astronomy), and that with variability of hours. One also observed correlated variability episodes with the optical and X-rays.

This gives hope that the basic physical mechanisms underlying these phenomena may be closer to an understanding; they may be even related after all, and also relate to many other high energy phenomena such as ZeV cosmic rays and cosmic magnetic fields.

Therefore the authors of this summary decided not to stand in the way of hot, new trends at a conference like this and gave rather unequal weight to the different topics, putting here more emphasis on these new developments.

2. High-Energy Astrophysics

2.1. Gamma-ray bursts (Waxman)

Gamma Ray Bursts (GRBs), short flashes of gamma-photons on the sky, have captured the imagination of theorists for decades after they were initially discovered by satellites to monitor nuclear explosions in space. Until early 1997 all we had were speculations. This changed dramatically when the Italian-Dutch satellite BeppoSax started to provide sufficiently good positions for new GRBs, that for the first time made radio, optical, and X-ray detections of

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their afterglow possible. The high point of these discoveries was the first redshift of a GRB [109,3], demonstrating that, in at least one case, the GRB came from a cosmological distance.

Pre-1997 properties of GRBs have been reviewed in Hartmann [55], and Fishman & Meegan [44]. They are isotropically distributed over the sky to all tests made (using the BATSE data from the Compton Gamma Ray Observatory), with the current catalogue of over 1100 bursts, have no repeaters as far as can be stated with certainty, and have a count-rate relation already suggestive of cosmological distances (a downward deviation from a –3/2 powerlaw in cumulative numbers at low flux levels). Their *typical* fluence is $\approx 10^{-5}\,\mathrm{erg/cm}^2$, which translates at cosmological distances to an energy required reminiscent of a supernova [138].

The modern theoretical attempts to interpret GRBs center on ideas by Mészáros and Rees [104–106,152, 130,131,107,108], as well as Paczyński [122–129]. In these models a relativistic shock is caused by a fireball expanding into a surrounding medium, such as the interstellar medium or a stellar wind (or jet?), accelerating electrons/positrons to a very high energy, which then produce the electromagnetic radiation observed in GRBs and their afterglow. The low level of associated radiation at other wavelengths limits the baryonic load (*i.e.*, the content in thermal protons, which would be expected to cause thermal radiation) of the emitting regions to very low amounts, and also constrains the scale of the emitting region to lengths much larger than a neutron star. It appears that all the emission seen is actually non-thermal.

Such models readily lend themselves to the modification to hadronic particle populations [188,189,181,182, 111,112,114,191,194], so as to accelerate also baryons to very high energy, and use the ensuing hadronic interactions to produce gammas as as well as high energy protons. It then becomes of interest to ask whether a combination of hypothetical models can be built, which produce both very high energy cosmic ray particles and the gamma rays which are observed.

We note that there appears to be no correlation between the arrival directions of gamma ray bursts [56,169] and the super-galactic plane (*i.e.* a 'local' galaxy over-density), in contrast to the finding for the very high energy cosmic rays [168,57,176] (see below). Also, there is no correlation between the gamma-ray bursts of the third BATSE catalogue as well as the pre-GRO bursts and the arrival directions of high energy cosmic rays from the Haverah Park set, covering approximately the same period of time [169].

Eli Waxman showed in his contribution that now quantitative models for the emission observed from GRBs are available which can be tested. He was able to provide a lengthy discussion of the recently detected GRB 970508, including the determination of a lower limit to its redshift (see also [191,194–196,192,193]). Other recent work is described in [107,108,130,131,174,175,184] [3,22,29,47,51,66] [78,94, 109,132,139] [156,157,183,45,115,129] and in IAU circulars. This list is only exemplary.

We briefly outline the essential features of the fireball model [107,192], considering for simplicity only the external shockwave propagating into the surrounding medium: A large amount of energy is released and starts an expansion with a highly relativistic velocity, of order $\gamma \approx 300$. Rather akin to the normal Sedov solution for supernova remnants, the heated interstellar medium dominates the expansion after the initial burst. There is a shell of relativistic matter with radius r, and thickness $r/(4\gamma^2)$ in the observers frame; the density in the shell frame is given by $n' = 4\gamma n$, and the internal energy $e' = 4\gamma^2 n m_p c^2$, disregarding any heavy elements. The heated energy of the ISM shell is $4\pi r^2(r/(4\gamma^2))\gamma^2 e' = E/2$ where E is the energy of the explosion, and the factor 1/2 comes from sharing the energy between ejecta and the ISM. The factor γ^2 in front of the internal energy in the shock frame e' derives from the transformation to the observers frame. This then gives the evolution of γ with time $\gamma \sim r^{-3/2}$, which—again—is rather reminiscent of the Sedov relation for the expansion velocity of a shock in the interstellar medium (*e.g.* [23]). Light is emitted over $t = (r/(2\gamma^2 c) \sim r^4$, and the electron population starts at the relativistic thermal energy $\gamma_{em} = \xi_e \gamma \frac{m_p}{m_e}$ with ξ_e being some factor of order unity. The electrons continue to higher energies with a powerlaw determined by the shock. The synchrotron emission has its minimum frequency at $\nu_m = \gamma\gamma_{em}^2(e_e B'/(m_e c))$, where e_e is the charge of the electron. This translates to

$$\nu_m \sim t^{-3/2}$$

and so the temporal behavior of the spectrum is expected to be

$$F_\nu \sim (\nu/\nu_m)^{-\alpha} \sim t^{-3\alpha/2},$$

where α is the spectral index of the synchrotron radiation. This is a testable case: For GRB 970228 the spectrum was determined between optical and X-ray wavelengths and gives $\alpha \approx 0.63$ and consequently the temporal behavior has a scaling as

$$F_\nu \sim t^{-0.95}$$

to be compared with an observed t^{-1} behavior. This is a magnificent and positive test and was one of the main points of Eli Waxman's lecture. At the time of writing the optical afterglow has been observed to fade steadily still after six months for GRB970228.

Particles can be accelerated at internal shocks in the GRB outflow, which may be responsible for the rapid variability in some GRBs [106]. Eli Waxman proposed that in the shocks produced by the explosion both electrons and protons get accelerated; the absolute limit to acceleration for energetic protons is the spatial constraint, assuming that acceleration is sufficiently rapid: $\gamma_p m_p c^2/(eB') < r/\gamma$, where γ is the Lorentz factor of the shock and the expression is in the shock frame. Scaling the magnetic field with the assumption of equipartition (introducing the factor ξ_B) in this model we get $B' = \xi_B \sqrt{8\pi e'} = \xi_B \sqrt{32\pi\gamma^2 n m_p c^2}$. This then leads to a maximum proton energy in the shock frame of

$$\gamma_{p,max} m_p c^2 = 2 \cdot 10^7 \, n^{1/2} \, \xi_B \, r_{17} \, \mathrm{erg}$$

using the empirical scaling for the numerical relationship between Lorentz factor and radius from radio observations [45] $\gamma = 3 \, r_{17}^{-3/2}$, where $r_{17} = r/10^{17}$ cm. The maximum energy written in the observers frame is then given by

$$\gamma_{p,max} m_p c^2 = 3 \cdot 10^{19} \, n^{1/2} \, \xi_B \, r_{17}^{-1/2} \, \mathrm{eV}$$

demonstrating that very high energies are possible. Going to the smaller radius, where the GRB event first becomes visible, near $5 \cdot 10^{15}$ cm, where the Lorentz factor of the shock is near 300, obviously we have there

$$\gamma_{p,max,*} \approx 10^{20} \, n^{1/2} \, \xi_B \, \mathrm{eV}$$

to within the uncertainties sufficient to account for the highest energies observed in Cosmic rays, if we accept $\xi_B \approx 1$. Of course, everything depends then on which density of the interstellar medium is relevant; if we take the density recently determined from ROSAT observations for the hot interstellar medium [164], of $\approx 3 \cdot 10^{-3}$ cm^{-3}, then the maximum energy is too small, but if we take the average density as determined from neutral hydrogen measurements of order 1 particle per ccm, then the proposal becomes viable. So, Eli Waxman argued that such high energy protons may account for the observed ultra high energy cosmic rays.

One serious question, however, is whether the overall energetics of the fireball are reasonable [158,24] or actually exceed the level given by any conceivable model of neutron star mergers or other stellar collapses.

Eli Waxman also went through the exercise to estimate the contribution to a universal high energy neutrino background, which we all hope to see soon with AMANDA at the South Pole.

Of course, the latest news from the May 8 burst which had come out the night before his lecture dominated everything. The observation that this burst was at cosmological distances, gives one of longest sought answers in Astrophysics of the last decade and is a quantum leap in our understanding of the enigmatic GRBs. With those observations at hand we can now for the first time test the quantitative predictions of models, like the one presented here.

2.2. TeV & ν-Astronomy (Rhode, Bean)

Besides GRBs, Blazars—presumably black hole powered relativistic jets, pointing at the observer—are the other main source of high-energy photons. They have now been observed at TeV energies, where they sometimes have their strongest electromagnetic output and also demonstrate extreme variability down to small fractions of an hour.

The key point of these TeV observations of Blazars is to decide which emission mechanism is the dominant one: are hadronic or leptonic interactions the basis for the high-energy emission? In the hadronic interaction model protons are accelerated to high energies.

Here, we assume a shock which accelerates protons and electrons and wish to consider what the maximum photon energy can be before Klein-Nishina effects or other losses cut off the spectrum for an observer. The shock velocity is taken to be U_1, the magnetic field strength B, the fraction of the homogeneous magnetic field energy in turbulence b, the natural logarithm of the wavenumber k range ratio of turbulence as $\Lambda = \ln(k_{max}/k_{min})$, then the maximum Lorentz factor for protons can be written as [14]:

$$\gamma_{p,max} = 7.4 \, 10^{10} (\frac{b}{\Lambda})^{1/2} \, \frac{1}{B^{1/2}} \, \frac{U_1}{c}$$

Here the maximum energy is limited by synchrotron losses and we have adopted a saturated spectrum of turbulence with k^{-1}, different from Biermann & Strittmatter [14]. We note, that using the limit of a relativistic shock velocity and setting all other parameters to their limits corresponds to setting the acceleration time scale equal to the Larmor cycle time, which would seem to be a rather extreme limit; however, in order to derive a strong upper limit, we will go to this limit below (see also the arguments on electron maximal energies regarding the Crab nebula by de Jager and Harding [68]). Of course, a strongly relativistic shock would modify this argument as seen from an outside observer [135]. Therefore, going to this absolute limit we will set $(b/\Lambda)^{1/2} \, (U_1/c) = 1$. The expression for the maximum Lorentz factor of electrons is $\gamma_{e,max} = 1.3 \cdot 10^7 \, B^{-1/2}$. The Klein Nishina cutoff becomes important when the photon energy in the frame of the collision approaches the rest mass of the electron, and so when $\gamma_e h\nu \approx m_e c^2$.

Including the Lorentz-factor of the bulk motion γ_j we obtain

$$(h\nu)_{lept,max} \approx 6 \cdot 10^{13} \, \mathrm{eV} \, B^{-1/2} \, (\gamma_j/10).$$

Now, the magnetic field strength is expected to approximately scale as $B \approx 10^4\,\mathrm{Gauss}\,(r/3\cdot 10^{13}\,\mathrm{cm})$.

Therefore, going to this rather extreme limit, and using the region close to the black hole, the maximum photon energy comes out to be

$$(h\nu)_{lept,max} \approx 6\cdot 10^{11}\,\mathrm{eV}\,(\frac{10^4\,\mathrm{Gauss}}{B})^{1/2}\,\frac{\gamma_j}{10}.$$

This is in fact quite close to the maximum derived in various models in the literature, *e.g.*, [26–28,19,163]. Therefore, should the observations conclusively demonstrate that the spectrum continues straight to above 10 TeV photon energy (for which there may be some indication), then the leptonic models would begin to have serious difficulties.

Going through the same argument with hadronic processes, we obtain $(h\nu)_{max} \approx m_\pi c^2 \gamma_{p,max}$ and so for the same parameters as above, this maximum is

$$(h\nu)_{hadr,max} \approx 7\cdot 10^{19}\,\mathrm{eV}\,\frac{1}{B^{1/2}}\,\frac{\gamma_j}{10}.$$

As a result, hadronic processes are much more readily able to account for photon energies in the high TeV range, *e.g.*, [87,88,95,96,98–101,91,97,118,117]. However, the present observations do not yet allow a final judgment on this question.

Protheroe & Biermann [144] argued recently that the infrared radiation field from the molecular cloud torus, expected to exist in all AGN in the "Unified Scheme", will terminate all TeV photons unless they are emitted above the torus, that is a distance from the central engine of order 0.1 to 1 pc. This argument is safe by a factor of 1000, *i.e.* even if the luminosity of the torus is 1000 times weaker, TeV photons still have a hard time to escape.

This means that many models in the literature would fail and especially the leptonic models would have problems. However, the feature used in many of these models, a small distance to the central engine, is not always essential, and so we can expect this class of models to get rejuvenated.

The final judgment will come from the high energy neutrino observations, which are a firm prediction of the hadronic models. In this vein, Wolfgang Rhode reviewed the current situation:

Within the last few years Blazars have been investigated with different techniques (satellites, Cherenkov telescopes, air shower arrays) above photon energies of more than 1 GeV. The high energy part (>10 TeV) of the spectrum is of special interest, as noted above. First, the detection of photons far above 10 TeV would favor accelerated protons as the primary high energy particles. Secondly, the distance up to which a >10 TeV photon can be observed depends on the density of infrared photons at $\approx 10^{-2}$ eV in the universe. An observation of a distance dependence of the high energetic photon flux from Blazars at various distances could thus provide the possibility to measure directly the cosmological density of the infrared (IR) background radiation [173], and therefore provide a crucial check on the early evolution of galaxies and their activities, both in their starburst mode as well as in their central activity [171].

It appears that modeling the observed gamma-ray background is consistent with a flat photon spectrum of index -2 [166] for the AGN responsible for the background, consistent with a typical spectrum for Blazars.

Mannheim *et al.* [102] investigated systematically a sample of 13 Blazars within the field of view of the HEGRA (High Energy Gamma Ray Astronomy) experiment, which were all close enough (z < 0.1) to be not absorbed at photon energies of several ten TeV. This sample was later enlarged to 30 sources.

The Whipple group discovered two Blazars, Mrk 421 and Mrk 501, at TeV energies [145,146]. These observations were confirmed by the two prototype telescopes (threshold about 1.5 TeV) of the HEGRA telescope array during the setup phase of the array [136,137]. Both groups also looked at other sources and established low upper limits [155]. In spring 1997 Mrk 501 was observed to show an eightfold flux enhancement over the last two months before the meeting (May 1997) which was still continuing[67].

The HEGRA telescope system observed Mrk 421 up to more than 5 TeV [79], and Mrk 501 up to about 20 TeV [59,137].

As reported elsewhere by a team led by Stefan Wagner [185,186] a campaign to simultaneously monitor the BL Lac object Mrk 421 at optical, X-ray and Gamma-ray wavelengths was done together with the ASCA-satellite and the Whipple observatory. The variations are correlated on time scales of one to several days. In one case the optical brightness has been observed to vary within 60 seconds, putting extreme constraints on any theoretical model.

Besides the two now famous sources, the sample of 30 Blazar sources was further investigated by the HEGRA team with several independent data sets and analysis techniques [93]. In autumn 1996 a possible detection of a cumulative signal and a marginal detection of the source 0116+319 in three of five data sets were reported by the HEGRA collaboration [110,154]. A test of the z dependence of the significance of the detection of all sources of these data sets suggests, that the detected TeV photons for individual Blazars with z>0.07 was consistent with zero significance, while the distribution of detection significances for TeV emission from z<0.07 Blazars was above zero—even though they individually did not reached the 5σ level. As already pointed out in [110] two other HEGRA data sets do not show this behavior. Such different results, nevertheless, are still consistent with the present knowledge of the highly variable time structure of the sources.

Including all systematic uncertainties, the mean maximum photon energy of the Blazars as a combined sample is expected to be between 30 TeV and 70 TeV. At higher energies a detection of signals from this object class would require a large surface array [102,197].

The detection of photons of Mrk 501 up to about 20 TeV now shows that the calculations of the infrared background given in [173] led to a severe overestimate of the IR photon density. As pointed out in [110] an independent upper limit can be tentatively calculated by using the fact, that only up to $z \simeq 0.07$ significant photon detection excesses were found in the Blazar sample. One obtains a IR-photon density close to the lower estimates of MacMinn and Primack [92]. This conclusion has recently been confirmed by a calculation of Berezinsky *et al.* [11].

The high energy TeV photons observed with both detector types (Cherenkov telescopes and surface array) seem presently to suggest that hadronic processes are required in Blazars; we note once again, that high-energy protons are in fact directly observed here on earth.

An ultimate test for many of these models is the detection of high energy neutrinos. Wolfgang Rhode briefly discussed some ramifications of the recent discovery [65] that the canonical model to explain the gamma-ray emission spectrum of our Galaxy—assumed to be produced by Cosmic Rays impinging on thermal gas and dust in the Galaxy—provides an excellent fit to the spatial variations, but a contradiction with the spectrum. It appears as if the cosmic ray spectrum responsible for the interaction (p-p collisions leading to pions which decay) is quite a bit flatter than the spectrum which is both indicated by direct observation and by radio observations of other galaxies. In an extensive collaboration involving groups at NASA, at Bartol, in Wuppertal and in Bonn, it has been shown, that using this inference one can predict anew the neutrino spectrum of the Galaxy giving a flux of neutrinos about ten times higher than expected so far. Hence through gamma-ray observations we can learn directly something about the in-situ properties of high-energy particles far away from earth.

As discussed by Francis Halzen in this volume, intense efforts are under way (AMANDA) to directly detect extragalactic neutrinos from hadronic processes in the universe. In this workshop Alice L. Bean reported on an alternative method to detect these by radio emission from air-showers in ice—the RICE experiment [2].

Consider a high energy (>100 TeV) neutrino coming from underneath the South Pole ice sheet, and causing an electromagnetic shower. This shower causes a radio emission pulse to travel in a cone-shaped surface through the ice. In the RICE experiment radio antennas have been lowered into the ice, and can pick up any such radio emission. RICE will consist of an array of compact radio (100 to 1000 MHz) receivers buried in the ice at the South Pole. During the 1995-96 and 1996-97 austral summers, several receivers and transmitters were deployed in bore holes drilled for the AMANDA project, at depths of 141 to 260 m. At present Alice Bean *et al.* are testing the setup with a receiver and try to develop algorithms to pick up any signal from the background. Only in coincidence with the AMANDA array can such a nice and old idea be fully developed and properly tested. If it works, it will be a great boost, because radio technology is well developed and mature.

2.3. Cosmic Rays (Biermann)

The absolute record holder in energy, however, are high-energy cosmic rays, for which the origin and transport through the intergalactic magnetic field were discussed by Peter Biermann:

The recent detection of several cosmic ray events with energies beyond 10^{20} eV is challenging astrophysical theories [10,46,162,15,116]. Theoretically, the microwave background does not allow particles beyond $\approx 5 \cdot 10^{19}$ eV to reach us from cosmological distances [50,198,172,1,9,147,48,149]. However, we now have a significant number of clear events of particles with energies beyond this limit even though these highest energy cosmic rays clearly cannot be contained in our Galactic disk and therefore must originate further outside. Biermann briefly sketched the various proposals to explain these high energy events, such as monopoles [74], the decay of exotic particles [12,162,25,153,72,142,143], shocks in the large scale structure of the universe [121,70], compact objects [61,161], Gamma-ray bursts (see above), large scale shocks in our Galactic halo [69], galaxy collisions [21], clusters of galaxies [71,32], active galactic nuclei [14,140], and, specifically, radio galaxies [14,151]. In any model in which the cosmic rays arrive from nearby cosmological distances, say, from sources related to galaxies, we can make some strong predictions: The clustering of arrival directions on the sky ought to correspond to the source clustering for energies at which intergalactic scattering by magnetic fields is no longer important, and for which the cosmologically local structure of the universe is still inhomogeneous. Above $4 \cdot 10^{19}$ eV the arrival directions of cosmic rays, as seen by the Haverah Park array [168], the Akeno array [57], and also by a combination of all experiments [176], are no longer isotropic, but appear to partially cluster towards the super-galactic plane, the locus of cosmologically nearby normal galaxies, and radio galaxies. Some local enhancements of the very high-energy cosmic rays may be due to several identifiable radio galaxies; one such candidate is the radio galaxy 3C134 [165].

On the other hand, using the known distribution of candidate sources such as radio galaxies [147,167, 148], and not just the simplified notion of the super-galactic plane [177–180,159,160], one can simulate the clustering of arrival directions [190,170]: One result is that the clustering to the super-galactic plane as derived from the source locations should be weak, and might not be seriously detectable with the statistics available.

Clearly the transport of Cosmic Rays [141] through the inter-galactic medium and knowledge of cosmological magnetic field strengths is important. Simulations [16,17] of the formation of cosmological structure, for example allow to determine the spatial inhomogeneity of cosmic magnetic fields. Such simulations, however, do not give an absolute number for the strength of the magnetic field. Combining these simulations with observations of the "Rotation Measure" (of polarized light) to distant radio sources allows then to deduce upper limits for the strength of the magnetic field. These upper limits are of order $0.2\,\mathrm{to}\,2\ \mu$gauss along the filaments and sheets of the galaxy distribution. In one case, the sheet outside the Coma cluster, there is a definitive estimate of the strength of the magnetic field consistent with this range [75,85]. Such estimates are almost three orders of magnitude higher than hitherto assumed, usually based on derivation using the same data, but assuming a *homogeneous* universe (which we know is wrong). High energy cosmic ray particles can be either captured or strongly scattered in such magnetic filaments and sheets, depending on the initial transverse momentum. The cosmological background in radio and X-ray wavelengths will have contributions from these intergalactic filaments and sheets, should the magnetic fields really be as high as $0.2\,\mathrm{to}\,2\ \mu$gauss. We conclude that the magnetic field structure in the universe is likely to be just as extremely inhomogeneous as the galaxy distribution. Hence, some fraction of highly energetic particles should be trapped inside the sheets of the baryonic matter distribution, and so produce the weak correlation with the super-galactic plane detected.

3. Relativistic Astrophysics

3.1. Black Holes and Relativistic Jets (Falcke, Wiita)

Heino Falcke reported on **Jets in AGN**: Astrophysical jets can be the largest and most impressive signs of the energetic phenomena one commonly associates with black holes and active galactic nuclei (AGN) and Heino Falcke reviewed our continuously expanding picture of those gigantic cosmic plasma accelerators.

In recent years it was found that, rather than only a minority of sources, almost all types of black holes seem to produce those outflows. Besides the well known radio-loud quasars and radio galaxies this includes radio-quiet quasars, Seyferts, LINERs, and X-ray binaries (stellar mass black holes) as well. Those jets can substantially influence their environment and are often the site for intense energetic phenomena, *e.g.* the production of gamma-rays and cosmic-ray particles of the highest energies known today. The energy-budget of those large, extended jets is probably mainly controlled by the accretion rate onto the central object and a still mysterious effect that causes a dichotomy in the jet emissivity relative to the accretion power. Heino Falcke discussed the evidence for astrophysical jets in various classes of AGN and their basic parameters which are crucial for the modeling of all energetic phenomena that have been linked to AGN.

It is often argued that the escape speed from the central object is an important factor that determines the terminal jet speed. If that is true and since we believe that most of the AGN are powered by a black hole one may expect that if an AGN produces a jet it should *always* be relativistic. Consequently the crucial question then becomes: Which classes of AGN have jets? In [33] and [34] the authors wrote down a hypothesis, simply stating that since black holes do not have many free parameters, AGN should be similar in their basic properties ("the universal engine", [36] and hence one should *ab initio* assume that all AGN have relativistic jets rather than only a few sub-classes. As it turned out, this hypothesis, in its simplicity, was surprisingly successful.

However, there are interesting difficulties: One finds a clear dichotomy between radio-loud and radio-quiet quasars and it is often assumed that the radio-quiet quasars do not have a relativistic jet at all, while VLA observations of the steep-spectrum radio-loud PG quasars [113] and [73] have clearly established, that those sources have large scale radio jets. Heino Falcke therefore asked: what would be the consequences, if radio-quiet quasars too would have relativistic jets? As for radio-loud quasars, the most prominent sources would be those which are pointing towards us and are relativistically boosted. In an optically selected sample, we would expect that, if radio-quiet quasars have relativistic jets, some of the quasars are accidentally pointing towards us, thus producing a population of 'weak Blazars' with a number of predictable properties. And indeed, Miller *et al.* [113] and Falcke et al. [35,41] were able to identify a small sample of radio-intermediate quasars (RIQ) which met all the requirements for being relativistically boosted, intrinsically *radio-quiet* quasars [42,40], thus strongly suggesting that in fact *all* rather than just 10% of quasars have relativistic jets.

Besides radio-quiet quasars, there is another important regime where one should find relativistic jets. Quasars are powered by black holes with high accretion rates, but what happens if the accretion rate decreases? Will those jets die completely? Ho *et al.* [62,63] found that roughly one half of all nearby galaxies show signs of optical activity in the nucleus, in the form of LINER or Seyfert spectra, and quite a number also show nuclear radio emission. This could indicate the presence of a black hole engine [58,38,39,43].

Falcke and collaborators conclude [43] that indeed the radio cores in LINERs are part of the central engine since optical and radio fluxes are correlated. Moreover, we can compare the radio and emission-line luminosities with the jet/disk model by Falcke & Biermann [37]. The model predicted a specific radio/nuclear luminosity correlation for low-power AGN and is based on the assumption that accretion disk luminosity and jet power in AGN are coupled by a universal constant. The LINERs fall exactly into the range predicted for low-luminosity, *radio-loud* jets.

This result not only strongly suggests that LINERs do have powerful nuclear radio jets (*e.g.* M87; NGC4258, [60]; M81, [18], etc.) but is also consistent with mildly relativistic Lorentz factors around $\gamma_{\rm j} \simeq 2$ as used in the model. That should be compared with Lorentz factors of $\gamma \simeq 6 - 10$ derived with the same method for radio-loud quasars [35].

Paul Wiita reported on work done with Gopal-Krishna and Vasant Kulkarni (both at the NCRA of the Tata institute at Pune, India) on the status of the so called "Unified Scheme" which is used to explain the differences of the most powerful radio jets just in terms of different orientation and obscuration:

A key argument in favor of orientation based unification schemes is the finding that among the most powerful 3CRR radio sources the (apparent) median linear size of quasars is smaller than that of radio galaxies, which supports the idea that quasars are a subset of radio galaxies, distinguished by being viewed at smaller angles to the line of sight. Recent measurements of radio sizes for a few other low frequency samples are, however, not in accord with this trend, leading to the claim that orientation may not be the main difference between radio galaxies and quasars. Wiita pointed out that this "inconsistency" can be removed by making allowance for the temporal evolution of sources in both size and luminosity, as inferred from independent observations. This approach can also readily explain the other claimed "major discrepancy" with the unified scheme, namely, the difference between the radio luminosity–size correlations for quasars and radio galaxies. Some of this work is reported in [80–82].

Black Holes: The scales of relativistic jets are still large compared to the event horizon of a black hole, but even black holes are slowly coming into sight! *E.g.* Falcke pointed out that the mass of the black hole in the center of our Galaxy is now determined with a very a high precision ($2.65(\pm0.2)\cdot10^6 M_\odot$) by the measurement of proper motion of stars [30], pushing the central dark mass density to $10^{12}\,M_\odot{\rm pc}^{-3}$ (*i.e.* the mass of a whole galaxy concentrated in less then the volume between the solar system and the next stars). Any alternatives to a black hole, *e.g.* an ultra compact cluster of stellar remnants seems to be ruled out now [103] thus making the Galactic Center source Sgr A* the best supermassive black hole candidate today. Interestingly, the mass is so large that the photon horizon of this black hole has a diameter corresponding to an angular resolution of 27 μarcsecond. Such a resolution will in fact be reached by planned VLBI (very long baseline interferometry) experiments operating at 220 GHz. Since this black hole also has an ultra compact emission region estimated to be of a similar size, radiating at just this frequency, this leaves the tantalizing possibility to directly image the horizon of a black hole at least in one case.

Paul Wiita also reported on work done with Gang Bao and Ying Xiong, (also at Georgia State University) and with Petr Hadrava (at the Astronomical Institute of the Czech Academy) on Polarization Variability as a Signature of Black Holes:

In regions where electron scattering dominates the opacity above accretion disks, X-ray radiation originating there should be partially linearly polarized. Both observations of rapid X-ray variability and theoretical studies suggest that this inner disk region is unstable and could appear clumpy. He showed how variations in the orbital parameters of the bright spots and the angle between the line of sight and the disk axis affect the observed polarization. The amplitudes of both the changes in the degree of polarization and the angle of the plane of polarization are energy-dependent. They are relatively independent of the physical mechanism producing the polarization. This feature is directly created by the gravitational bending of light rays by the central black hole and it is apparently unique to a system including a black hole and an accretion disk. This work is reported in [4,5].

3.2. Ultrahigh magnetic fields and extreme densities (Kennedy)

Dallas Kennedy reported on work done with K. S. Gopinath (U. Florida) and J. M. Gelb (U. Texas) on relativistic Landau states of electrons in intense astrophysical magnetic fields, encountered especially in neutron stars at $\gtrsim 10^{12}$ Gauss (LANL astro-ph/9702014 and astro-ph/ 9703108).

The classical and semi-classical orbits of relativistic charged particles were outlined for motion on a spherical surface, in an intense magnetic dipole background. The dipole and rotational axes in general should not be aligned, if the star's magnetic dynamo is to be self-sustaining. Kinematic regimes differ depending on the relative sizes of energy, canonical azimuthal angular momentum, and magnetic field strength in rescaled units. Magnetic flux enclosed by the orbits is quantized very close to the poles. Open questions relating to the state of electronic matter near neutron star surfaces were sketched.

Subsequent work has extended this calculation to the full 3-D problem at finite density, with electrons in local field-transverse planes, but including the gravitational and hadronic structure only as given backgrounds (LANL astro-ph/9707196).

Further questions include the magnetically-induced structural changes below the star surface and changed state of matter, as well as observational signals of such exotic "quantum Hall-like" surface physics.

4. Cosmology

A larger and perhaps more entertaining review was given at this conference by Rocky Kolb. Here we summarize some of the interesting twists to cosmological models presented during the astrophysics workshop.

4.1. Fluctuations in the early universe (Hochberg, Berera)

David Hochberg reported on Course-Graining, Structure Formation and the Transition to Large-Scale Homogeneity in the Universe [52,53,8,49,64,6]:

Newtonian hydrodynamics plus FRW cosmology combine to yield a good description of the matter dominated Universe at large scales. Under assumptions of vorticity-free flow and validity of the Zeldovich approximation (that the gravitational acceleration is parallel to the velocity) the ensuing dynamics can be recast in terms of a cosmological version of the (massive) Kardar-Parisi-Zhang (KPZ) equation, which has enjoyed extensive application in the study of surface growth phenomena. Here, he applied it to the problem of the growth and distribution of large-scale structure in the Universe. Using the well established techniques of the dynamic re-normalization group to study the scaling properties of the solutions of the KPZ equation, he calculated the power law behavior and attendant exponent of the galaxy to galaxy correlation function and showed that the transition to large scale homogeneity is an necessary consequence of the course-graining.

Arjun Berera reported on an attempt to determine the largest scale of primordial density perturbations beyond the Hubble radius with COBE-DMR and the implications for early universe cosmology:

Causality imposes rigorous constraints which suppress super-horizon scale coherence. The power spectrum of scalar primordial density perturbations is modified by inclusion of a super-Hubble suppression scale in order to respect this constraint mandated by causality. A recent analysis of COBE-DMR data was presented, in which measurements were made of the super-Hubble suppression scale, the spectral index and the amplitude. Theoretical implications of this analysis focus on the warm inflation scenario, which in part motivated this COBE analysis. A summary of the scenario was presented which included discussion about self-consistency, avoidance of a re-heating period, relevance to open universe and primordial seeds of density perturbations and magnetic fields.

Although the details of the scenario are model dependent, this so identified regime is an outcome only of Friedmann cosmology. He asked if this modification would have any significant effects on the mechanisms to produce large magnetic fields.

As mention in the previous Cosmic ray section, the origin of magnetic fields is still an elusive goal in our understanding of the universe; many models have been proposed, from dynamos working in stars, in accretion disks, in entire galaxies, and in large scale accretion flows; primordial magnetic fields have many attractive features, since they may obviate some of the difficulties faced by the dynamo models.

4.2. Magnetic Fields in the Universe (Kronberg)

Recently improved instrumental capabilities over the past decade or so have greatly improved our knowledge of the extent and strength of cosmic magnetic fields. Some surprising discoveries have emerged and Phil Kronberg summarized our latest knowledge of the strength and extent of magnetic fields in galaxies, galaxy clusters, and what little inkling has been gained about widespread intergalactic magnetic fields. The status of our knowledge is well described by Kronberg [85,86] in two excellent reviews.

Phil Kronberg included some basic theory of magnetic field regeneration, and some constraints imposed by recent experimental data. Kronberg also explained the observational methods of probing magnetic fields in outer space, and mentioned future prospects linked to experiments with gamma- and cosmic ray detectors, and at low frequency radio and sub-millimeter bands.

The information came from measurements of the Faraday rotation of the plane of linear polarization turned by the transfer through an ionized and magnetized medium. This rate of angle rotation with increasing wavelength is defined as Rotation Measure (RM) (radians/m^2), and is proportional to the integral of the electron density along the line of sight, folded with the parallel magnetic field components. On the sky most of the effects are dominated by our own Galaxy. Looking further one finds the following:

a) In normal galaxies such as our own the magnetic fields are of order 3 to 10 μgauss [7], with a lower limit of about 1 μgauss.

b) In the halo of our Galaxy the magnetic field is $\approx$ 0.2 μgauss, over a scale of a few kpc [54].

c) In starburst galaxies such as M82 the magnetic field can be very much stronger, with values up to $\approx$ 30 μgauss possible [83].

d) In clusters of galaxies the magnetic field strength is subject to some uncertainty in the number of magnetic field reversals along lines of sight through the cluster [76,77,85], but the overall rotation of the polarization plane of background radio sources suggests values of a few μgauss, while some cooling-flow clusters with strong radio galaxies are known to have values about ten times higher.

e) Outside one cluster, the Coma cluster, Kim *et al.* [75] have estimated the strength of the magnetic field near 0.1 μgauss, assuming equipartition between magnetic fields and relativistic particles.

f) Across cosmological distances there is only an *upper limit* of $\approx$ 1 nanogauss, derived from Rotation Measure data measured along lines of sight to cosmologically distant radio-quasars [85], assuming a reversal scale of the magnetic field structure of 1 Mpc, and otherwise cosmologically homogeneous properties of the intergalactic medium. If we were to assume that the reversal scale is the same as the bubble structure of the galaxy distribution, then this limit would be $\approx$ 200 picogauss.

g) We do not (yet) have a successful theory to account for the origin of cosmological magnetic fields, neither in galaxies, nor in clusters. Stars such as the Sun show evidence for a fast dynamo acting to reverse the magnetic field every 11 years, and so it is often assumed, but has not finally been demonstrated, that galaxies do the same on the much larger scale [7]. In clusters of galaxies, the magnetic field can energetically be provided by the radio galaxies [85,32].

The observation of normal magnetic fields in a galaxy at fairly large redshift suggests that magnetic fields can build up over cosmologically fairly short time scales [84]. On the other hand, the strength and topology of magnetic fields in galaxies appears to exclude an origin as simply primordial [134,7]. One recent attempt to simulate the growth of cosmological magnetic fields has been made by Kulsrud and collaborators [90], using the structure formation itself as the source in a battery process [13]. Another argument has been that massive stars and compact accretion disks in AGN may be all that is needed, also starting with a battery process [15].

4.3. Cosmological Birefringence (Ralston)

Finally, Ralston reported on his much debated claim of cosmological birefringence, published with Nodlund.

Ralston asked the question, whether there is birefringence of the universe, based upon an analysis of radio galaxy data [119]. If so, this would have been a major change for our understanding of the universe [89]. He finds a big effect for redshifts larger than 0.3 from a large database of previously published measurements of polarization vectors of galaxies. While the proposal has spawned an intense debate with a number of counter examples on the LANL electronic preprint server [187,20,31,120,150] and in the popular press, Ralston himself concluded "Barring hidden systematic effects, the analysis indicates a new cosmological effect". Clearly the debate demonstrates, that most researchers still would put more weight on the first part of the sentence and favor a systematic effect in the analysis of the data to interpret Nodland's & Ralston's findings, before making drastic changes to existing cosmological models.

5. SUMMARY

Compact objects from the centers of the Gamma Ray Bursts to the the presumed black holes at the focus of the AGN span about ten powers of ten in mass. Their associated outflows, whether explosive, non-steady, steady or quiescent, have been the focus of much work over the past several decades. Those are the laboratories where new physics can and will be learned. It appears that basically the same concepts may help us to understand much of what we observe: Everywhere we look at a compact object such as a black hole, there seems to be an accretion flow (disk) and a jet, with gigantic and relativistic shock waves running through these jets, and accelerating particles. Another common analogy is simply the formation of a compact object with a concurrent explosion, be it as a supernova, or as a Gamma Ray Burst. In the case of a Gamma Ray Burst again a relativistic flow seems indicated, and we come back to the basic AGN language, and maybe the same physics.

Many questions still remain: Are the ZeV energy particles, presumably protons, really derived from shock waves in such jets from the most powerful radio galaxies we know? Or do they come from the Gamma Ray Bursts? Or, most excitingly perhaps, do they come from the decay of particles of GUT-scale energies?

Are the emissions that we observe in Gamma Ray Bursts or in TeV Blazars, all derivable from leptonic processes, or do they require hadronic processes to get started? What will neutrino astronomy bring us?

Can we connect all these observations to the structure formation of the universe, whether it is the cosmic magnetic fields or the first seeds of black holes?

These and many more tasks are waiting for us and thanks to impressive developments in recent years, *we can be certain that the "Golden Years of Astrophysics" are not over yet.*

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