Particles and Fields in Radio Galaxies: A Summary

R. D. Blandford
130-33 Caltech, Pasadena, CA 91125, USA

Abstract. A summary is presented of a meeting on Particles and Fields in Radio Galaxies held in Oxford in August 2000. Recent detailed studies of radio maps and the first X-ray images from Chandra X-ray Observatory, together with new capabilities in simulating hydromagnetic flows, are transforming our understanding of how jets are formed by accretion disks orbiting massive black holes, how these jets dissipate and how they inflate the giant radio-emitting lobes by which they were first identified. As they can be imaged in such detail, extragalactic radio sources remain central to the study of jet outflows in general although there is a strong convergence with corresponding studies of Galactic superluminal sources, gamma ray bursts and young stellar objects.

1. Introduction

This meeting, which was planned as a specialist discussion on the details of emission mechanisms in extragalactic radio sources, was held at a propitious time. The first X-ray images of jets and their associated lobes from Chandra X-ray Observatory had just been released and, just as was the case when linked and very long baseline radio interferometry became possible and when we learned of the prodigious $\gamma$-ray powers of blazars, a whole new chapter in the eighty year old study of jets is being started. The study of extragalactic radio sources has also changing in a quite different sense because the jet phenomenon is turning out to be far more common in its astronomical expression than extragalactic astronomers ever expected, as it is now known to be a common accompaniment to young stellar objects and an occasional by-product of accretion onto compact stars.

Nevertheless, the main topics of discussion at this meeting mostly centred around the radio study of extragalactic jets and I have chosen to organise this somewhat impressionistic summary using a series of general questions that have been around for a while and where, although we don’t yet have answers, we are making progress. I will use the convention of referring to contributors using [ ] and defer to these authors for original references.

2. Jets
2.1. Why do Accreting Sources Form Jets?

If I follow the logic of the theorist as opposed to that of the observer, this is the first question to ask and it is one that was implicit in many of the theoretical papers. A somewhat non-standard answer is that when sources accrete, the gas that they collect almost certainly possesses far more specific angular momentum than the accreting object and almost all of this must be off-loaded. Now, ever since the first discussion of disks in binary and proto-stars, we have been acutely aware that there has to be a strong torque that accomplishes this task and we now know that this torque is almost always hydromagnetic in character. The gas forms a disk flow and the differential rotation drives the exponential growth of magnetic field on a dynamical time, until it, too, is dynamically important. As matter flows in, angular momentum flows out; at least that is what has been conventionally assumed. However, it need not all flow out. Disks have a lot of surface area and there may be an appreciable divergence in the angular momentum flux due to surface magnetic torque. After all, the sun, a very slow rotator by the standards of an accretion disk, has managed to lose a significant fraction of its initial angular momentum though the solar wind in this manner. Although we do not understand how much of the disk angular momentum escapes through this channel, a jet, or more generally, a bipolar outflow, may be simply Nature’s way of removing unwanted angular momentum.

The torque, \( \Gamma \), must also do work at a rate \( \Gamma \Omega \), where \( \Omega \) is the angular velocity. Not only is angular momentum transported outward through the flow, so is energy. In fact, if the gas is gravitationally bound, there must be a divergence of this flow of energy. In a traditional accretion disk, this is the source of the radiant energy and this explains why the energy release in simple models is three times the locally liberated binding energy. However, not all flows will radiate efficiently and if they don’t we have a second possible answer to the question. Jets (or, more generally, outflows) are the next best way to remove the energy from the disk when radiation is not up to the job.

Disks are not the only possible sources of power and the central object can contribute significantly. In the case of massive black holes in AGN, the rotational energy of the hole – surely ample to re-supply the most profligate of radio lobes – can be extracted with modest efficiency using electromagnetic field. This can be directly released in a jet core in the form of Poynting flux [Meier, van Putten, Begelman] or, alternatively, transmitted to the inner disk. In the former case the energy released is likely to have a low baryon fraction and be in an ideal state to power ultrarelativistic jets. Even if the central object is very slowly rotating, as appears to be true of protostars and many neutron stars, there is still as much orbital kinetic energy to tap from the innermost disk orbit as has been released in the form of binding energy up to this point.

Given these different options, the question becomes “How much energy flows along each of these channels under different circumstances?” We know that hydromagnetic jets do not always remove all the angular momentum and energy, despite the fact that there is no dynamical objection to this happening. After all disks are prodigiously luminous as quasars and binary X-ray sources. Perhaps, all disks lose some angular momentum and energy in this manner but that it is only those that need to get rid of energy – specifically those whose central masses are so large as to render the mass supply rate sub-critical and thermal electron
heating ineffectual – that produce the most efficient disk outflows. In addition, perhaps it is only those sources where the central hole (or star) spins fast that create high speed flows and that both factors are necessary to form high power ultra-fast jets.

2.2. How do Accreting Sources Make Jets?

Following this theoretical tack, there has been much progress, some of it reported at the meeting [Begelman, Meier, Trussoni, Hughes] towards developing an understanding of the global behaviour of disk magnetic fields. The issue is really that the sort of investigations that are possible analytically are usually artificially limited to assumptions like high symmetry and self-similarity and these can be quite misleading. Furthermore, even if we acknowledge that some simple solution of the equations of MHD is formally unstable, this may be misleading because nonlinear saturation can limit its importance. Magnetic field is famously slippery and any time we have been able to observe it in action – in the heliosphere or the plasma laboratory – it has demonstrated far more imagination than us. For this reason, the widespread use of three dimensional MHD codes (in some cases, general relativistic) is a great advance. True, they have to leave out a lot of the physics like reconnection, radiation, Alfvén wave damping and so on, but still they allow us to perform quite novel experiments which sharpen our intuition as to what is possible.

If one accepts, as most now do, that jets and outflows are fundamentally relativistic and hydromagnetic, there are still several options. (An important exception may be BALQ and even Seyfert outflows which are sub-relativistic and appear to be associated with objects radiating near to the Eddington limit [Wilson].) Jets can be powered by the disk or the hole, or both. Jets may be launched centrifugally or through pressure, magnetic, radiative or gas. They may be collimated by an organised toroidal field, as is found in the solar wind, or by a much more disorganised assembly of twisted field loops. All of these models have had enthusiastic proponents and simulations are sharpening the debate. As observations of nearby jets reach down to smaller radii, $\sim 100m$ in the case of M87 [Sparks].

New phenomena, like magnetic switching [Meier] have been discovered. Perhaps we are learning that hydromagnetic jets are intrinsically episodic and that we have been leaving out a key ingredient when we have taken the easy way out, at least in analytical modelling, by seeking stationary solutions to the flow equations. Surely the observations – of QPOs in GRS1915+105, of superluminal expansion in compact quasars and of Herbig Haro objects – support this interpretation.

A key concern is “Can a disk maintain a large scale, poloidal magnetic field or will this field migrate outward under resistive diffusion faster than it is convected inward under flux-freezing?” Another fundamental physics concern is what happens to the energy that is dissipated in a disk at a rate $G\nabla\Omega$? Does it all feed a hydromagnetic wave turbulent cascade being damped at small length scale through wave-particle interaction? Alternatively, does it get converted into heat through magnetic reconnection? Should we introduce a second parameter $\alpha'$, that takes account of the dissipation? These considerations are also directly
relevant to the jet flows themselves where linear velocity gradients take the place of differential rotation.

This leads me to the admission, that every theorist who has worked in this field must make, which is that the study of jets is an empirical, observational business at least when we try to go much beyond fundamental conservation laws. (Not all astrophysics is likely this!) There is a level of detail in the radio maps which we can try to describe but which we would not have predicted from first principles. If this proposition needs defense, and in a meeting attended mainly by observers I doubt if it does, then the recent Chandra images of the X-ray nebulae surrounding the Crab and Vela pulsars should surely make the point. In both cases, isolated, spinning, magnetised neutron stars are, quite unexpectedly, able to create apparently well-focused outflowing jets presumably without the aid of a disk. They also show evidence for large scale, transverse shocks and equatorial ring structures. Magnetic fields are again the best way to try to explain the observations. (The equatorial ring-like structure might be attributable to a current sheet formed in an outflowing wind, analogous to what happens with the solar wind.) However, we do not yet know how this happens.

As we cannot answer any of these basic MHD questions through theory alone and so we must turn to the laboratory. The sophistication of the diagnostics of the terrestrial magnetosphere and, especially, the solar corona, through the YOHKOH, SOHO and most recently TRACE spacecraft, is truly impressive. There is a wealth of data, publicly available, that is large ignored that ought to contain answers to some of these questions. Let me give two examples. It appears that most of the reconnection in the solar flares takes place on the small scale, in nanoflares, rather than in the giant flares that disrupt communications and so on [Beckert]. If the same is true of an accretion disk corona then this has serious implications for our view of how a disk corona is heated. If we look at the solar wind, we find that it emerges from a gas whose temperature does not exceed 2 million degrees and yet it can achieve outflows speeds in excess of 800 km s$^{-1}$. It is launched neither thermally or centrifugally. Perhaps it is sent on its way by acquiring the momentum of outflowing hydromagnetic waves. Observations are starting to settle these matters in some generality.

2.3. How do we “see” Jets?

A jet is an expanding outflow and as such the natural synchrotron emissivity should decline rapidly with radius. The rate is model-dependent, of course, but is generally much faster than observed [Giovannini]. For this reason, it has been assumed that there is in situ particle acceleration along the jet. This fits in well with the notion that jets are naturally episodic, perhaps on account of instabilities that develop near their sources. These instabilites will naturally develop into internal shocks as the flows are hypersonic. They will also be responsible for an overall deceleration of the flow as deduced on spectral grounds [Laing]. In addition, the termination shocks are associated with hot spots [Brunetti, Hardcastle].

Now non-relativistic shocks appear to be responsible for transmitting a power law distribution of relativistic ions and electrons in supernova remanants through diffusive Fermi acceleration. According to the basic theory of this process, the efficiency is high and the back pressure associated with the reflected
ions may provide a negative feedback on the process. However, we still do not have a good theory of the magnetic turbulence that can explain how particles are back-scattered [Chandran]. (It may soon be possible to run hybrid particle-fluid simulations that will address this problem directly. In addition, the observational front, the failure to detect TeV $\gamma$-rays from some young supernova remnants has been interpreted as implying that many remnants do not conform to the theory of shock acceleration and that extra factors are required to account for the overall spectrum of Galactic cosmic rays.

A central theoretical problem with shock acceleration is that we do not have a generally accepted understanding of particle injection. We do observe that electrons appear to be injected into the acceleration process at a slower rate than ions. Undoubtedly the plasma physics is quite complicated and Bernstein modes provide a plausible way to control this process [Dendy].

It appears that most of the compact sources that we observe, as well as a good fraction of the type II extended radio sources, are energised by relativistic shocks. The standard theory of Fermi acceleration [Quenby] cannot apply here because the energy changes in a single shock passage are not small. Nonetheless the problem can be well-posed if sufficiently stringent assumptions are made about the transport. This problem has recently been solved by several groups and a logarithmic slope of 2.23 derived for the particle energy spectrum [Kirk]. It is not clear how relevant this is when the shock normal speed exceeds $c\cot\theta$ and it is not possible to transform away the electric field. However it certainly represents an important advance and provides a basis for addressing the next problem which concerns the effect of the back reaction on the accelerated particles mediating the shock structure.

It is no less important to understand how magnetic field is amplified at a shock front. We fully expect that there will be adiabatic compression at a non-relativistic shock so that the rms field shock strength will increase by a factor $(\sin^2\theta + r^2\cos^2\theta)^{1/2}$, where $r$ is the compression ratio and $\theta$ is the angle between the magnetic field direction and the shock normal. ($r = 4$ for a non-relativistic strong shock in ionised gas.) However, it has commonly been assumed, for example in studies of gamma ray bursts, that the post-shock field rapidly builds up to a significant fraction of the equipartition value [Birkinshaw]. This can orders of magnitude larger than the compression value. I do not think that there is any good understanding of what to use in any of these environments. Although there have been suggestions of post-shock turbulence in studies of supernova remnants, it has more commonly been assumed that field amplification occurs around the generalised contact discontinuity where the shock interstellar medium interact directly with the ejecta from the supernova explosion. The fact that we find it so hard to locate the bounding shock fronts around supernova remnants, whereas we commonly observe the non-thermal synchrotron emission in the form of a diffuse, expanding ring, supports this view. Perhaps relativistic shocks are different. Pulsar nebulae, containing ultrarelativistic, hydromagnetic shocks are the best laboratories that we have to study, in situ particle acceleration in an environment believed to be similar to that in extragalactic, relativistic jets and gamma ray bursts.

The global evolution of the magnetic field is also highly relevant. There is increasing evidence for helical field structure in the observed jets [Laing, Gabuzda],
though it is quite unlikely that this field can be unidirectional. The total magnetic flux that would be necessary to make this happen is far larger than could ever be confined in the vicinity of the central black hole. Again, our understanding is very primitive.

The new images of X-ray jets presented and discussed here [Harris, Wilson, Worrall, Sparks] are full of surprises. Most encouragingly, they appear to be quite common and some patterns are starting to emerge [Birkinshaw]. In addition, Pictor A is strikingly well-collimated and it was particularly reassuring to see the jets and lobes of Cygnus A revealed in this manner.

However, the interpretations were quite varied. The case is well made that there is no simple common explanation for the emission. Synchrotron radiation (requiring the acceleration of 100 TeV electrons) [Harris], inverse Compton emission (of local synchrotron photons, the ambient, external radiation field [Brunetti] and the microwave background radiation[Tashino]) and, perhaps even in a few cases, bremsstrahlung or proton synchrotron radiation [Protheroe] can all occur under different conditions. Most importantly, there is a working, synchrotron-inverse Compton model of the integrated spectrum that makes a lot of sense in relation to what we know about radio jets [Celotti].

In retrospect this should not be a surprise. After all, we directly observe jets on scales from milli- to Megaparsecs and over a wide range of physical conditions when different emission mechanisms can dominate. As the cooling times of the relativistic electrons are generally quite short compared with the dynamical times, the X-rays provide an invaluable probe of the conditions within these sources. The effects of relativistic Doppler boosting, which we now take for granted, are also turning out to be quite subtle [Celotti]. This is also not surprising because it is easy to highlight a dynamically insignificant part of the source when it is directed towards us [Hardcastle]. These are early days in the study of X-ray jets.

We have recently had cause to question the assumption that the radio emission from compact radio sources is due to the synchrotron process. The measured “variability” brightness temperatures can be nine orders of magnitude above the standard inverse Compton limit. Although we are no longer intimidated by the large bulk Lorentz factors that are implied ($\Gamma > 10^3$) - gamma ray bursts have released us from our inhibitions - the derived radiative efficiency is likely to be impossibly low. For this reason, there has been considerable attention paid to the influence of refractive scintillation on variability. There have been some exquisite observational investigations [Dennett-Thorpe, Jauncey, Wagner] which have demonstrated that the observed variations are “sins of transmission”. However the source brightness temperatures still have to be challengingly large ($> 4 \times 10^{13}$ K corresponding to $\Gamma > 30$ in the best studied case and probably much larger in other cases). The motivation for considering alternatives to synchrotron emission remains and shock fronts, which we know can lead to ring-like particle distribution functions that are far from equilibrium together with high energy densities of plasma wave modes, are natural sites for non-linear conversion to electromagnetic modes and maser emission [Bingham]. These possibilities deserve further study.
2.4. What are Jets?

It is a matter of considerable embarrassment that we still cannot identify the working substance in the jets. This material is surely not immutable. Just as we are confident is the case in the Crab Nebula, the energy is probably changed from an electromagnetic form to a pair plasma to an ion plasma and (at least partially along the way into photons). We expect that this also happens in jets. However we do not have a good understanding of where the transitions occur and, in particular, what we are observing using EGRET, VLBI, MERLIN and the VLA!

The reason why something like this must happen at small radius is that radiation drag is catastrophic unless there is an alternative carrier of momentum to pair plasmas. The only two plausible candidates are protons [Protheroe] and Poynting flux [Meier, Begelman]. The former has always seemed rather problematic because it is not at all clear how to get the high energy protons in the first place (shocks only randomise the energy that is already present), without invoking an even greater energy density in electromagnetic field. This field may also have to be invoked to collimate the outflow. If electromagnetic field is present the electric fields are likely to be so strong that relatively small inductive effects will create a non-zero \( \vec{E} \cdot \vec{B} \) which will break down the vacuum by creating copious electron-positron pairs, just as is envisaged in a pulsar magnetosphere.

The final conversion to an ionic plasma seems equally inevitable because a jet must have an outer radius and it seems very hard to prevent some measure of entrainment of the surrounding plasma along its length, even if it is protected by a cocoon of backflowing plasma [Laing, Simkin].

There are three more direct, observational arguments that have been advanced in favour of pair plasmas being present in the radio emission regions. Firstly, the presence of circular polarisation now in over twenty sources like 3C279, where the the Faraday rotation appears not to be too large [Wardle] is very difficult to explain without appealing to a pair plasma. (It is difficult to rule out synchrotron emission completely as the cause but the frequency-dependence is not as predicted.) The second argument is dynamical [Celotti, Harris]. The estimated jet powers are excessive if the relativistic electrons that have to be invoked to carry the emission carry protonic, as opposed to electronic, baggage. The third argument is quite ingenious and comes from the analysis of narrow emission lines formed when jets impact interstellar clouds. The line ratios are not as predicted by conventional ionising agents and may indicate that relativistic particles are at least partly responsible. It may be possible to distinguish positrons and protons by following this approach. However, none of these arguments is, as yet, watertight, though there is every reason to be optimistic that they will strengthen with more X-ray and, ultimately, \( \gamma \)-ray observations.

Of course if the presence of pair plasma can be demonstrated, this very much strengthens the argument that jets are powered by spinning black holes.

3. Lobes
3.1. What is a Lobe?

The short answer to this question has been known since the early 1970s. A lobe is the repository for all the energy that is left over after the momentum of a jet has been exhausted pushing away the intergalactic medium. It is the fact that the speed of the jet is much greater than the speed of advance of the lobe that leads to this surplus.

We are now able to study lobe morphology in considerable detail and able to address much more sophisticated questions. The key to understanding the overall energetics of radio sources is to measure the pressures within and around the lobes. This can be done using X-ray observations. However, it appears that the total energy density in the lobes can significantly exceed the absolute minimum energy density required to account for the measured synchrotron radio emission; the difference probably being made up with high energy electrons [Leahy, Blundell].

3.2. Lobe Energetics

Radio sources do have a pronounced effect on the overall appearance of many clusters and large “holes” can be seen in the X-ray maps that correspond to the location of the radio lobes [Fabian]. The characteristic shapes of prominent radio lobes, like those associated with Cygnus A, may be a straightforward consequence of the jet dynamics and reflect the overall stability of the jet [Eilek, Rudnick]. The sharply-defined boundaries that are seen are important because they set an empirical upper bound on the rate at which relativistic and thermal plasma can mix [Owen, Rudnick, Reynolds]. Unfortunately, many of these X-ray maps are turning out to be very complex and, as we do not know the three dimensional distribution of the gas, it is going to be quite hard, in practice to interpret the Sunyaev-Zel’dovich maps with much precision.

A recent development is the advent of hybrid codes that are not only able to trace the hydrodynamical evolution of a jet, together with its associated lobe, but can also follow the passive transport of magnetic flux and relativistic particles accelerated in shock fronts [Tregellis, Jones, Marcowith]. Large scale magnetic field amplification and turbulence evolution can also occur [De Young]. Although the models will never correspond in detail to individual sources, there is some optimism that we will be able to understand the rules by which particle energisation and transport and field amplification take place under relativistic conditions. As is the case with jets, not all of the particle acceleration appears to be associated with strong shock fronts. Ongoing particle acceleration at sites other than strong shock fronts, is often required because the radiative loss timescales can be shorter than the source lifetimes and backflow times [Laing]. Magnetohydrodynamic turbulence, perhaps associated with noise from the supersonic jet provides a very plausible source of the long wavelength waves that can energise the particles in the lobes. Adiabatic compression can contribute to the re-energisation under some circumstances [Ennslin].

3.3. When did Lobes Form?

The ability to trace the lobes to very low surface brightness is starting to allow us to understand the “archaeology” of double radio sources. In sources like M87, it is, in principle, possible to trace the history of nuclear activity for the past
Gyr [Begelman]. The large scale, low radio frequency structure of this source is actually reminiscent of a “mushroom cloud” and could arise for essentially the same reason [Kaiser]. This is particularly interesting because, in this example, we know, from the mass of the central black hole ($\sim 3 \times 10^9 M_\odot$), that the source was almost certainly once a quasar, although probably not recently. At the very least, the source behaviour has been quite variable [Binney]. It is likely that the lobe will rise in the cluster gravitational field under buoyancy, until it finds a static equilibrium state.

Spectral aging studies of radio lobes are becoming increasingly sophisticated [Blundell, Rudnick]. Although particle and field injection is controlled by the hot spots, whose power declines with time, there is much more going on. Again, the validity of equipartition [Leahy, Hardcastle] and the possibility that the emitting plasma have a small filling factor [Manolakou] is again under debate. At the very least, the dangers of interpreting inadequately resolved radio maps are now quite clear.

4. What is the Environmental Impact?

The Chandra observations of clusters appear to corroborate the view that, in many rich clusters, the central cooling times are short compared with the age of the universe. What happens next remains controversial. The most natural consequence is that gas rains down upon the galactic nucleus. However, in several cases, we are not seeing the evidence for cooler gas. There have been several suggestions as to how to prevent this from happening. The gas may be reheated by intergalactic supernovae (although these are not observed) or low energy cosmic rays. Alternatively, there may be a large turbulent, magnetic or cosmic ray pressure.

This last possibility seems particularly interesting and has broader implications. The hot gas that we observe in clusters, groups and elliptical galaxies has presumably been heated by passing through a shock front; there really is no alternative. This is generally supposed to be an accretion shock located at the cluster periphery. However it could be that there is also a dense network of intergalactic shock waves and that most gas is heated there. These intergalactic shocks are quite likely to arise because the sound speed in the ionised (Ly$\alpha$ cloud) intergalactic medium is $\sim 10$ km s$^{-1}$, whereas the characteristic random motion of field galaxies (including our own) is several hundred km s$^{-1}$. The ionised gas that we observe at high redshift seems to disappear and it is unlikely that it forms stars and galaxies with extreme efficiency. A far more plausible fate is that it is rendered effectively invisible by heating to a million degrees. (Although it is possible that FUSE or XMM-Newton may find most of the local intergalactic medium, we will probably have to wait until the next generation of X-ray telescopes is launched). The intergalactic medium may be just as active and as interesting as the interstellar medium has been shown to be. Now if Galactic supernova remnants are any guide, then the transmited partial pressure in GeV ions by these shocks may be comparable to the pressure of thermal gas [Jones]. This will alter our estimates of the total static pressures in clusters and, consequently, radio source energetics. More interestingly and
importantly, it is possible that these cosmic rays will inhibit inflow after cluster gas starts to cool.

5. How Important are Extragalactic Radio Sources?

Although the study of extragalactic radio sources retains its intrinsic interest, it is (or should be) attracting the attention of a much larger community. The most timely connection is to the study of gamma ray bursts. These are now commonly (though still not securely) modeled as ultrarelativistic beamed outflows - jets. Many of the principles that were debated and discussed twenty years ago in the present context are being recapitulated in connection with gamma ray bursts [Rees]. There are, however, some important differences. Firstly, burst powers (typically estimated to be \( \sim 10^{44} \) W sterad\(^{-1}\)) are many orders of magnitude larger than the strongest quasar jets (up to \( \sim 10^{40} \) W sterad\(^{-1}\)). Secondly, the power is generally impulsive and so, although quasars are increasingly regarded as episodic, there is usually a pre-existing channel for them to propagate along. This difference is responsible for the observation of discrete afterglows associated with bursts, which overlap in the case of jets. Thirdly, the variability times observed in gamma ray bursts are very much shorter than in their AGN counterparts and this implies that GRB sources are much more compact. This implies much larger initial Thomson and pair production optical depths which, in turn, are responsible for the larger terminal Lorentz factors. However, the difference appears to be only one of degree.

Most tantalising of all, though, are the reports of considerable iron line emission [Rees]. If true, this is probably a big clue to the identity of the underlying sources. Otherwise, the similarities in and debates about the source models energy pathways and emission mechanisms are quite strong and there is a convergence between the two research fields which should be exploited. For example, now that attention has settled on jet models of gamma ray bursts, it probably becomes necessary to consider oblique relativistic shocks as the emitting elements. This will have a significant impact on the kinematics. Conversely, if we are really observing jets with \( \Gamma \sim 300 \) in bursts, then this should help us decide if really are observing flows with comparable speeds in AGN.

Another overlap, surprisingly not represented at this meeting, is the study of the Galactic superluminal sources into which some gamma ray bursters may eventually evolve. So far, the best Galactic cases have only exhibited modest superluminal expansion speeds, though this could be a selection effect. Perhaps we have to explore other galaxies to find micro-3C273’s. The advantage of studying such, sources, if they do exist, is that they vary and cycle on timescales that are six to eight orders of magnitude shorter than their quasar counterparts and observers would get far more immediate gratification if they could observe such sources. For example, we are awash with data on QPOs in the best studied case, GRS1915+105, whereas it has proved very hard to identify corresponding phenomena despite thirty five years of quasar monitoring. The same may happen with relativistic jets.

A further possible point of contact that was discussed [Watson], is the origin of ultra high energy cosmic rays - protons, presumably, with Lorentz factors up to \( \sim 3 \times 10^{11} \) and energies of 50 J, comparable with that of the shot with which
I was caught out in the cricket match. These particles have lifetimes against photo-pion production in the microwave background of only a hundred million years. This tells immediately that their luminosity density is quite large, in fact comparable with the average cosmological luminosity density of $\sim \text{GeV}$ cosmic rays.

There are two classes of explanation – that they are left over from the decay of much higher energy particles, almost certainly formed cosmologically, or that they are accelerated from lower energy, just like all the other cosmic rays. The former explanation is surely the more exciting. However, there appears to be a serious objection to it. It is very hard to avoid producing gamma rays in far greater profusion than protons and these can be distinguished statistically by their zenith angle distribution. They are not seen. Furthermore, the same electromagnetic channel is likely make a much larger TeV gamma background than is measured (Coppi, private communication). For this reason interest has returned to “conventional” astrophysical models. Most of these models require potential differences $\Phi > 3 \times 10^{20} \text{V}$ in order to accelerate the very highest energy particles and have associated powers $L > \Phi^2/Z_0 \sim 3 \times 10^{38} \text{W}$, where $Z_0 \sim 377\Omega$, is the impedance of free space. One of the few source candidates we have that satisfies the proximity and power requirements is the powerful extended radio galaxies. (Black holes and compact jets are capable of accelerating ultra high energy cosmic rays but have too large an ambient radiation energy density to allow them to escape.)

My final example of the new relevance of extragalactic radio sources brings me back to the start of this summary. Outflows from active galactic nuclei may also provide a feedback that strongly influences, limits or even initiates galaxy formation. Perhaps relativistic jets can deposit enough energy or momentum in the surrounding gas to prevent disk formation in elliptical galaxies and in cooling flows in the centres of clusters. Now radio sources themselves may not be quite up to this job. In fact it has been shown that the gas surrounding the radio lobes in at least one clusters is actually cool not hot [Fabian, Reynolds]. However, hydromagnetic disk winds and, especially broad absorption line outflows could be more powerful and have a major impact. After all the nuclei of most powerful radio sources and central dominant galaxies in clusters almost surely passed through one or more quasar phases in the past and we expect that most of the energy that was released will be during a hyperactive, quasar phase.

This general idea has been rather controversial, mainly because of its subversive implications for the current standard model of galaxy formation. However, it is still worth exploring with numerical simulation. Perhaps the real “purpose” of outflows from accreting sources is to limit their gas supply to a manageable rate.

6. Peter Scheuer 19??-2001

While completing this summary, I learned of the passing of Peter Scheuer. Through his own major research contributions, his gentle yet incisive questioning and his selfless encouragement of others, Peter had a lasting influence on every aspect of this meeting and on most of the contributors. This article is dedicated to his memory.
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