Part 1

Introduction

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The Phenomena of High Energy Astrophysics

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Abstract. A brief summary of some highlights in the study of high energy astrophysical sources over the past decade is presented. It is argued that the great progress that has been made derives largely from the application of new technology to observation throughout all of the electromagnetic and other spectra and that, on this basis, the next decade should be even more exciting. However, it is imperative to observe cosmic sources throughout these spectra in order to obtain a full understanding of their properties. In addition, it is necessary to learn the universal laws that govern the macroscopic and the microscopic behavior of cosmic plasma over a great range of physical conditions by combining observations of different classes of source. These two injunctions are illustrated by discussions of cosmology, hot gas, supernova remnants and explosions, neutron stars, black holes and ultrarelativistic outflows. New interpreations of the acceleration of Galactic cosmic rays, the cooling of hot gas in rich clusters and the nature of ultrarelativistic outflows are outlined. The new frontiers of VHE γ-ray astronomy, low frequency radio astronomy, neutrino astronomy, UHE cosmic ray physics and gravitational wave astronomy are especially promising.

1. Two Decades of High Energy Astrophysics

There has been a wonderful decade of discovery in high energy astrophysics. Accretion disks surrounding massive black holes in active galactic nuclei (AGN) have been traced into relativistic regimes using ASCA, Chandra and XMM-Newton (*e.g.* Fabian 2002, Wilms et al. 2001). Other disks around similar sources create ultrarelativistic outflows, or jets, that have been directly imaged on scales from pc to Mpc using HALCA and the VLBA (*e.g.* Junor, Biretta & Livio 1999), and Chandra (*e.g.* Wilson, Young & Shopbell 2001) and, indirectly, probed on sub–pc scales using EGRET (*e.g.* Hartman et al. 1992) and atmospheric Cerenkov telescopes (*e.g.* Quinn et al. 1998). Similar jets and disks have been associated with Galactic X-ray binaries (XRB) and shown to exhibit Quasi-Periodic Oscillations (QPOs) using, especially, RXTE (*e.g.* van der Klis 1998). Gamma Ray Bursts (GRB) were placed at cosmological distances following observations by BATSE (Meegan et al. 1992) which was confirmed by ground-based spectroscopy of X-ray afterglows discovered by Beppo-SAX (Costa et al. 1997, Metzger et al. 1997). These bursts also appear to comprise collimated, ultrarelativistic outflows which eventually form the afterglows discovered by Beppo-SAX and which, in turn, presumably evolve to form a small fraction

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of the supernova remnants (SNR) whose dynamics and composition have been mapped at X-ray energies (*e.g.* Canizares 2002). The X-ray background was effectively associated with individual faint sources by ROSAT (as confirmed by Chandra and XMM-Newton, *e.g.* Hasinger 2002, Brandt et al. 2002). Evidence of the hot intergalactic medium (IGM) has been found by FUSE (eg Tripp, Savage & Jenkins 2000) and, more recently,reported with Chandra (*e.g.* Fang et al. 2002) and we are now studying this same gas in rich clusters of galaxies in fine spectroscopic detail (*e.g.* Mushotzky 2002)

These (electromagnetic) discoveries have been matched by great discoveries in cosmic ray physics. The atomic and isotopic composition of cosmic rays has been measured in exquisite detail by ACE and the spectrum has been extended to ultra high energy (UHE) by the AGASA and HiRes arrays. In addition, neutrino mass has been detected by painstaking work at Homestake, Kamionkande, SNO and KamLAND (*e.g.* Eguchi et al. 2003).

These examples, which could surely be matched by a quite separate list involving different sources and observatories, are, arguably, as far-reaching and of equal popular interest to the great discoveries that have been made over a similar period in cosmology and extra-solar planets.

The coming decade should be no less exciting. Integral has just been launched. Auger and Hess, which will detect UHE cosmic rays at ZeV energy and VHE γ-rays at TeV energy with unprecedented sensitivity, are just coming on line. Swift will study GRBs and produce a long overdue hard X-ray survey. Astro-E2, has a planned 2005 launch and will perform high dispersion spectrosocopy of accretion disks etc. This will be followed quickly by GLAST which should be roughly 50 times a powerful as EGRET. There are ambitious plans to open up high energy neutrino astronomy by augmenting AMANDA and constructing IceCube. LIGO is already operational and it is hoped that it will start gravitational radiation astronomy. There is also optimism that the space missions, Constellation-X/XEUS, LISA and EXIST will be started by the end of the decade.

hat this impressive list of operating and planned missions also brings out is that high energy astrophysics is an integrating discipline. Sources are observable over $\sim$ 70 octaves of the electromagnetic spectrum (including the single octave claimed by optical astronomers!) from $\lesssim$ 100 MHz to $\gtrsim$ 10 TeV. If we look forward to gravitational and cosmic ray astronomy, the spctrum expands to fill the interval from $\lesssim 100\mu$Hz gravitons to $\gtrsim$ 1 ZeV protons and the number of octaves doubles. High energy sources are invariably nonthermal which implies that they must be observed "holistically". Panchromatic campaigns to study AGN have been common for more than twenty years and, more recently, multiwavelength observations have been the key to the study of GRB afterglows.

There is a second, integrating feature of high energy astrophysics and this has been less appreciated and, so far, less exploited. This is that much of what we can observe depends upon a fairly small number of physical processes that we do not understand very well. However, these processes should be source-independent. Examples include the behavior of ultrarelativistic shock fronts, the rates of thermalization and the thermal conductivity of hot magnetized plasma and the viscosity of shear flows. Ultrarelativistic flows, in general, are seen in AGN jets, pulsar wind nebulae (PWN) and GRBs and there is every

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reason to undertake comparative studies to understand their general, global, behavior. The rate of particle acceleration and magnetic field generation at a relativistic shock front ought to depend solely on the Mach number (or, equivalently, the Lorentz factor). Hot plasmas are observed in the laboratory, in the solar corona, in the inter-planetary, -stellar and -galactic media. Most of the important transport processes should scale simply with density and in an unknown, though universal manner with temperature. The effective angular momentum, mass and energy transport in strongly, shearing media, likewise probably depends on a set of elementary principles. Here, numerical simulations are starting to be especially instructive. I expect that exploiting the wide variety of physical conditions in cosmic sources to divine fundamental scaling relations will be a major feature of high energy astrophysics research over the next decade.

2. The Cosmological Context

The recent maturation of observational cosmology has special implications for high energy astrophysics. There now exists a cosmological framework in which to interpret the observations. Although we do not understand much at all about why this is the case, we do appear to inhabit a universe with Hubble constant $\sim$ 65km $s^{-1}Mpc^{-1}$ age, $\sim$ 14 Gyr, a flat spatial geometry, and a current composition of roughly 70 percent dark energy, 25 percent dark matter and 5 per cent baryonic matter. This knowledge, allows us to be much more quantitative when analyzing individual sources, especially when estimating pressures, densities, speeds etc.

High energy observations have contributed significantly to the development of this framework. The most important example is the measurement of the matter density by observing the X-ray emission from clusters of galaxies. This has consistently given a value of roughly $\Omega \sim 0.3$ for a decade (predicated on the theory of big bang nucleosynthesis) and it is now claimed that the measurement error is better than ten percent (Allen, Schmidt & Fabian 2002. This same analysis led to an equally important value for the density fluctuation normalization, $\sigma_8 = 0.7$.

One example of the importance of being quantitative is in understanding the growth of massive black holes in AGN. The most recent determinations of the black hole mass density in contemporary galactic nuclei concludes that holes have to be assembled quite efficiently (with efficiencies $\epsilon \sim 0.2$, Yu & Tremaine 2002) and therefore radiatively. Furthermore, the discovery of powerful quasars at redshift $z \sim 6.5$ (Fan et al. 2001) implies that the first black holes probably grew at a rate faster than the Salpeter rate, simultaneous with the growth of the host galaxy. This, in turn has implications for the contribution of quasar ultraviolet radiation (probably small) to the intergalactic, photoionizing radiation field. There is a good possibility that GRBs will be seen to even greater redshifts than quasars and provide different probes of intervening material.

Another connection between high energy astrophysics and cosmology involves VHE γ-rays which constrain the mid-far infrared background. A complementary constraint is provided by the highest energy cosmic rays whose range is similarly limited by photopion production on the microwave background. Here

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we know the opacity very well and it it is the sources whose location is unknown, but must lie within ~ 30 Mpc at the highest energies detected.

3. Hot Gas

The two best laboratories for studying transport processes at high temperature are rich galaxy clusters and supernova remnants. Recent X-ray observations of both of these have been impressively detailed and are still far from digested.

3.1. Clusters of Galaxies and the Intergalactic Medium

Clusters are important cosmologically because as we have just seen, they are thought to be large enough to provide a fair sample of the baryons and because they are very convenient tracers of the growth of large scale structure that can be identified at large redshift through X-ray surveys, Sunyaev-Zel'dovich effect studies and weak lensing investigations. They are also important because they harbor the oldest galaxies at a given cosmic time and provide the best fossil record of the formation of the first galaxies.

Clusters have become important physically because they can teach us about the microphysical behavior of hot plasma. This has been become central to attempts to resolve the "cooling flow paradox". It has been known for a long while that the radiative cooling times of the gas at the centers of rich clusters is often shorter than the cluster ages. It was then supposed that the gas would flow into the central cD galaxies at rates as high as $\sim 1000 \mathrm{M}_{\odot} \mathrm{yr}^{-1}$. What appears to be happening is that the gas starts to cool more or less as anticipated, but then it almost vanishes only to reappear at much lower temperature radiating optical and ultraviolet emission lines copiously from gas with $T \sim 2 \times 10^4$ K and density $n \sim 100$ cm^{-3} (*e.g.* Peterson et al. 2003).

There are some important clues as to what is going on. The gas that is observed at high temperature appears to be in thermal equilibrium and the isotherms are nested quasi-spherical surfaces. Another important clue has emerged from studies of clusters like the Perseus and Virgo clusters that contain double radio sources. The X-ray emission from the areas of the sky occupied by these radio sources is reduced, suggesting that the the strongly magnetized, relativistic plasma responsible for the radio emission does not, in practice, mix well with the cooler (*i.e.* with temperature $\sim 10^8$ K!) plasma into which it is expanding. This inference has been reinforced by the discovery of fossil radio sources, presumably associated with earlier phases of nuclear activity, that are rising under buoyancy in the cluster gravitational field (*e.g.* Fabian et al. 2002). Some additional deductions have been made, rather more controversially. The gas immediately surrounding these bubbles is actually cooler than most of the cluster gas. The existence of these large temperature gradients in rich clusters argues that the effective mean free paths of hot electrons are smaller than given by Coulomb scattering in unmagnetized plasma. Most attempts to account for the thermal structure of clusters have posited some form of heating to prevent the gas from cooling. This seems rather unpromising. Piling gas up at a temperature where it can radiate relatively efficiently does not seem a good way to make it disappear! Also the radio sources, the most promising sources of distributed heating, do not appear to perform this function.

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I would like to propose a rather different explanation for these observations. The gas that accumulates in rich clusters has a very high entropy relative to the $\sim 10^4$ K gas that was ionized when the universe was ~ 0.5 Gyr old. The most likely source of this entropy is passage through a strong shock front formed as galaxy-sized perturbations become nonlinear and drive gas with sound speed ~ 10 km s^{-1} together with speeds ~ 300 km s^{-1} (*e.g.* Miniati et al. 2000). (Supernova explosions and expanding, double radio sources can also create strong shock fronts.) The post-shock gas will have a density $\sim 10^{-3}$ cm^{-3}, a temperature $\sim 10^6$ K and a pressure $\sim 10^{-12}$ dyne cm^{-2}. Now a gravitationally-induced shock in the IGM should behave just like one of similar Mach number ($M \sim 30$) in the ISM (see below). This implies that there should be a large, post-shock, cosmic ray partial pressure, roughly ~ 0.3 times the total pressure (*e.g.* Miniati et al. 2000). As the gas expands, following the passage of the shock, and as a consequence of the general expansion of the universe, the cosmic ray pressure will become slightly more important and may even dominate. However, if and when this gas collects into a deep potential well formed by a rich cluster of galaxies, the gas will be compressed and the cosmic ray pressure will decrease relative to that of the gas. The gas that is observed to be cooling in centers of rich clusters has a pressure similar to that in post shock gas and the $\sim$ GeV cosmic ray pressure is still likely to contribute about ~ 30 percent of the total. These cosmic rays should make clusters into $\sim$ GeV γ-ray sources, detectable by GLAST. Nonthermal emission from the electrons may have also been seen in the extreme ultraviolet (*e.g.* Durret et al. 2002). Finally, careful modeling of relaxed clusters using X-ray, lensing and microwave background observations may lead to detection of a pressure deficit in the thermal gas.

When the cluster gas starts to cool, as it must eventually, it will compress by a factor of a few until the cosmic pressure dominates and resists further compression. The gas will then cool roughly isochorically and the inflow will be halted or at least seriously inhibited. It is then possible for the cool gas to permeate the warm ($T \sim 10^7$ K) gas and radiate away the internal energy contained in the warm gas. In principle, this can be very efficient. Suppose that the cool gas has a temperature $\sim 10^5$ K, where its emissivity is maximized (*cf.* Krolik 1999), and a pressure of $\sim 10^{-10}$ dyne cm^{-2}, typical of the center of a rich cluster. $\sim 3 \times 10^7$ $M_\odot$ of cool gas occupying a fraction $\sim 10^{-5}$ of the volume suffices to radiate the missing soft X-ray power in the ultraviolet.

The problem is one of getting the energy from the hot gas to the cold gas fast enough. The traditional approach is to suppose that the interface is a static, conductive atmosphere. If the conductivity is dictated by Coulomb scattering then it scales $\propto T^{5/2}$ and the thermal contact is poor unless the cool gas is seriously overpressured with respect to the warm gas. However, this may not be the right description of the gas. The situation is likely to be quite complex for a variety of reasons. Firstly, the dynamical situation, may become unstable to Rayleigh-Taylor instablity. In addition, the galaxies that move almost sonically through the cluster, will be followed by large turbulent wakes containing streaks of cool gas that has been stripped from galaxies.. Finally, the ongoing aggregation of large groups of galaxies will drive large oscillations in the cluster gas. The gas is likely to end up quite well-stired so that the warm gas flows past the cool gas on a timescale short compared with the conductive time so that the electrons may not be in local thermodynamic equilibrium. To give a

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quantitative example, the electrons in the warm phase have speeds $\sim 10,000$ km s^{-1} and a Coulomb mean free path ~ 30 pc in the warm medium. It is therefore possible that the warm electrons may be brought closer to the cool gas by turbulent mixing than a mean free path and they are thereby able to come into direct contact with it. With this arithmetic,the Coulomb heating rate can now just balance the cooling rate of the cool gas.

A small quantity of cool gas, co-existing with the hot gas may then act as an effective heat sink, removing heat non-radiatively from the hot gas and radiating it away at a lower temperature. Understanding the heat transfer is central to understanding the mass flow. In the simple theory of evaporation, an inward conduction of heat is balance by an outward energy flux, $5Pv/2$. and the cloud evaporates. However what is envisaged here is that that there is a volumetric heating which is roughly balanced by radiative cooling. If the cooling exceeds the heating, there will be a steady condensation of hot gas onto the cool cloud; if the heating dominates, there will be evaporation. This may be self-regulating. Clearly a much more careful investigation is called for to see if the above sketch has any validity.

There has also been progress in studying the hot intergalactic medium outside clusters that recapitulates the progress that was made in understanding the interstellar medium following the launch of the Copernicus satellite. FUSE has observed local IGM in emission at a temperature $\sim 10^5$ K. and both Chandra and XMM-Newton have reported detections of hotter gas in both the local and the distant universe with temperature that may be as high as $\sim 5 \times 10^6$ K, although the interpretation of these observations is not yet consistent. The state of the IGM is a good monitor of the development of both large scale structure and stellar activity in the expanding universe. This is because the IGM is probably only heated to a temperature $\sim 1 - 2 \times 10^4$ K after reionization (which probably occurs when the universe is ~ 0.5 Gyr old following the formation of the first massive stars, Bromm, Coppi & Larsen 1999).

3.2. Supernova Remnants and the Interstellar Medium

If we had never seen supernovae or their remnants but had access to ultraviolet observations of hot stars, we would ask similar questions of the interstellar medium. However, we now know that it is the explosions of massive stars and not gravitational action that keeps most of the volume of the Galaxy at a temperature of nearly a million degrees. However, the details of how this happens are controversial. Most importantly, we do not understand how the bounding shock waves behave. We are not sure how the post-shock electron and ion temperature depend upon the Mach number and how quickly these two components equilibrate. The indications are that the most of the energy flux is carried by the ions and that the electrons are heated at rates that reflect Coulomb scattering, but we need to be more quantitative.

The acceleration of Galactic cosmic rays has long been associated with supernova remnants. Most of the cosmic ray energy density is in the form of ~ 1 GeV particles and models of the particle acceleration suggest that typical high Mach number shocks transmit a cosmic ray partial pressure that is $\sim 0.1 - 0.5$ times the total momentum flux. However, the observational evidence is confusing. On the one hand, ASCA observations of SN1006 first showed the

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presence of a nonthermal component in the X-ray spectrum which was taken as *prima facie* evidence that relativistic electrons were accelerated by some shock waves. However, there are other remants where the TeV γ-rays might have been expected and these are not seen, suggesting that the maximum energy to which the particles are accelerated is well below $\sim$ 1 TeV. Ion acceleration, can be detected though π^0 γ-rays. which may be seen by Hess, VERITAS and GLAST and has been reported by Enomoto et al. (2002), (but see Reimer & Pohl 2002).

It is also of quite general importance to understand how magnetic field behaves at shock fronts. The nonthermal emission that is measured may only require a simple compression of the pre-shock magnetic field so that its energy density is ignorable. A much greater stretching of the field is likely to occur in the vicinity of the contact discontinuity where the ejecta from the stellar envelope interacts with the circumstellar medium. A combination of radio polarization, optical and X-ray observations should again furnish some quantitative answers.

As a further illustration of how important it is to mobilise all the high energy observations to try to figure out the principles which govern the behavior of high temperature plasma, let me introduce a second "cosmic ray" paradox relating to the acceleration and propagation of Galactic cosmic rays. It is known that the observed cosmic ray spectrum has an energy-dependence $N(E) \propto E^{-2.6}$ and that the energy dependence of the observed spectra of secondary elements like Li, Be, B is steeper than that of the primary particles, $N(E) \propto E^{-3}$. This implies that the grammage traversed by cosmic rays before they escape varies with energy as $\lambda \propto E^{-0.4}$ and, consequently, that the sourced spectrum of the primary particle satisfies $S(E) \propto E^{-2.2}$, approximately. This is just what is expected in simple views of shock accleration theory and was one of the strongest arguments for taking it seriously. However, the observed primary spectrum extends all the way up to the famous "knee" in the spectrum around 1 PeV. This is inconsistent with the observation mentioned above that some supernova remnants only accelerate particles to much lower energy. It may also be incompatible with the measured cosmic ray anisotropy. This can be estimated by the ratio of the column density of the local interstellar medium $\sim 1 - 2$ mg cm^{-2} to the grammage $\lambda(E)$ traversed. The observed anisotropy at high energy may also be too small to be compatible with the standard power law model.

A possible resolution of this paradox is that individual SNR accelerate cosmic rays with power law spectra up to energies in the interval $\sim$ 0.1 TeV to $\sim$ 1 PeV so that their collective effect is to produce a quite convex source spectrum $S(E)$. If this is now combined with a propagation model in which $\lambda(E)$ has a compensatory concave shape. In other words, the grammage does not continue to decrease as a power law with increasing energy, but saturates. The quotient of the source spectrum and the grammage then, coincidentally, leads to a single power law spectrum. This leads to a prediction that the light element spectra should be concave. Whatever the true explanation, if we can understand on the basis of empirical arguments like this how cosmic ray protons and electrons are accelerated by shock waves and how they propagate, then we can export this understanding to the IGM.

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4. Supernovae

The spectacular imaging spectroscopy of supernova remnants of many different types by Chandra is starting to address many of these questions and should supply plenty of forensic evidence to enable us to reconstruct many of the details of the initial explosion, through studies of the distributions of the different elements (Canizares 2002).

SN 1987a was a touchstone for our understanding of core collapse supernovae (*e.g.* Michael et al. 2002). It produced the first detected supernova neutrinos and a pleasing affirmation of the most fundamental principles of advanced stellar evolution. However, it also provided some surprises. The absence of hydrogen from its intial spectrum led to its intial identification with a Type Ia supernova. However it clearly is a variant on the Type II supernova known as Type Ib and is characterized by the absence of a hydrogen envelope on the presupernova star.

There were other surprises. The γ-rays were observed far earlier than expected suggesting that the ejecta become highly inhomogeneous very quickly. SN1987a is coming back into prominence as its blast wave is just now encountering the equatorial ring of matter left behind by outflow associated with the pre-supernova star.

Now GRB are currently most fashionably associated with Type Ic supernova in which the helium envelope has also been stripped away. There are many puzzles raised by this model, foremost among them is the nature of the medium into which the relativistic blast wave, that forms the afterglow, expands. Consideration of what is observed in SN1987a could be quite instructive for models of GRBs. In particular we do not understand when neutron stars are left behind and when black holes form. More fundamentally, we do not have a widely accepted, working model of how any core collapse supernova model works. It is possible that some of the features of GRB models could, contrariwise, provide the missing ingredient for the Type II case.

5. Neutron Stars

Most neutron stars are observed long after formation. They are seen as XRB and they appear to be over-represented in globular clusters and this is attributed to three body dynamical stellar exchanges and recycling. The relative formation rates of neutron stars and black holes is also attracting some attention as three microlenses have been discovered where the lens is argued to be an unseen star with mass well in excess of the upper limit for a neutron star. This suggest that single black holes might be quite common in the halo of our Galaxy. These holes will be rather hard to detect by other means unless they have mass-losing companions — the accretion rate from the interstellar medium is probably too small to be of interest.

Neutron stars have long been regarded as cosmic laboratories where Nature allows us to witness experiments performed upon cold nuclear matter, that complement the experiments performed on hot nuclear matter at heavy ion colliders, exploring physical conditions that are otherwise inaccessible. There have been

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several, recent reports, some of them quite controversial, of new observations of extreme physical conditions associated with neutron stars.

Several soft gamma repeaters, exemplified by SGR 1806-20, have been identified with magnetars, slowly rotating strongly magnetized neutrons stars. In the case of SGR 1806-20, the surface field strength is measured as $\sim$ 80 GT while the rotation period is $\sim$ 8 s, ensuring that the observed emission cannot be rotation-powered. This contrasts with the X-ray pulsar SAX J1808.4 3658 which has a measured period of $\sim$ 2.5 ms approaching that of the fastest radio pulsar.

Observations of the surface temperature are also important. In the case of RXJ1856.5 -3574, a temperature of $\sim$ 0.7 MK has been measured and a very small radius $R \sim 7$ km inferred, provoking the suggestion that this could be a quark star (Drake et al. 2002). However, the case is quite unconvincing as it depends upon an uncertain distance measurement and a particular spectral decomposition (Braje & Romani 2002). For the central pulsar in the 821 year old supernova remnant 3C58, the temperature is below 1 MK (Slane, Helfand & Murray 2002). This is cooler than is computed on the basis of standard, modified URCA cooling calulations. This could be an indication that there is a pion or a kaon condensate in the core of the star. Alternatively, the proton fraction might be large enough to allow direct URCA cooling to take place (*e.g.* Yakovlev et al. 2002).

Finally, the X-ray source 1E1207.4 -5209 (Sanwal et al. 2002) exhibits two helium absorption lines which may allow the neutron star surface potential to be measured. As most neutron star masses have a pretty standard value $\sim$ $1.4 - 1.5$ $M_\odot$, this allows the radius to be guessed and the equation of state above nuclear density to be constrained.

6. Black Holes

There has been equally exciting activity in the study of black holes. Quasi-periodic oscillations (QPO) have been measured in several XRB, mostly associated with the accretion disk. It is clear that there is a very rich phenomenology to be understood, that encodes the mass and spin of the hole and which should allow general relativity to be tested. Unfortunately, there is still no widely accepted theory of QPOs that allows these identifications to be made. Normal modes of oscillation of specialized disk models have been computed. However, there is not an easy way to see how they can be excited and sustained at observable amplitudes and numerical simulations do not exhibit discrete modes like these. In addition, it is highly unlikely that the oscillatory X-ray emission arises from the photosphere of the disk. Their spectra are far too hard for this. Instead, it seems more likely that they are produced in an active corona. This requires there to be a strong coupling, presumably magnetic, to exist between the disk and the corona. If this is correct, then it certainly complicates the interpretation of QPOs.

There has also been a lot of attention paid to the Fe Kα lines, originally reported by ASCA in Seyfert galaxies. These are now seen in XRB. Occasionally these lines are quite broad, which has been widely attributed to a combination

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of Doppler shift and gravitational redshift. There are some puzzles. Most lines are seen as narrow and it is not known why and when they turn out broad.

The most extreme example is MCG 60-30-15, where the line can extend from 2-6.5 keV. This has been interpreted in terms of a model where spin angular momentum from the spinning black hole is extracted by the disks, with magnetic torques.(The energy released by steady, viscous disk accretion alone cannot account for the line profiles.) If this interpretation carries the day, then it supports the idea that relativistic jets are powered by black hole spin.

If additional evidence can be mustered for massive black holes spinning rapidly, then this has some interesting implications for their genesis. The point is that if black holes are built up by merging, as has often been proposed, then a retrograde capture of a small hole by a large hole will involve a larger transfer of angular momentum than a prograde capture (*e.g.* Hughes & Blandford 2003). Therefore, black holes that grow by merging will generally spin down rather than up and rapidly spinning holes are unlikely to be assembled in this way. This is all consistent with the most recent comparisons of the density of local black holes needed to account for the $z \sim 2$ quasar light and the local hole mass density computed using the hole mass — bulge velocity dispersion.correlation.

6.1. Adiabatic Accretion

Much attention has recently been devoted to what happens when gas is supplied to a hole at a rate much less than the Eddington rate. It has long been known that if the viscosity is relatively large and the electron heating not much faster than Coulombic, then the radiative efficiency is low and the gas will continue to heat up on an accretion timescale and will form a thick accretion disk or torus. In fact, a similar outcome is possible when the gas supply rate greatly exceedcs the Eddington rate. In this case, the radiative efficiency will be high but the radiation will be trapped by the accreting gas and the radiation pressure will support the thick disk. Either case can be described as "adiabatic accretion", by analogy with the nomenclature used to describe supernova remnants.

There have been three models proposed to describe adiabatic accretion. Advection-Dominated Accretion Flows (Narayan & Yi 1994) are steady flows in which all the mass that is supplied crosses the event horizon. Convection-Dominated Accretion Flows (Quataert & Gruzinov 2000), are non-stationary and the mass supply backs up. In ADiabatic Inflow-Outflow Solutions (Blandford & Begelman 1999), most of the energy that is released close to the hole is carried off in an outflow, usually, though not necessarily, involving a mass losing wind. In this case, the mass accretion rate will be much less that than the mass supply rate.

Perhaps the greatest challenge to these models is presented by our Galactic center (Baganoff et al. 2001). Here we know the black hole mass ($\sim 2.6 \times 10^6 M_\odot$) and can make an estimate of the mass accretion rate ($\sim 10^{21}$g s$^{=1}$). The bolometric luminosity is $\sim 10^{36}$erg s^{-1} and so the radiative efficiency relative to the mass supply is only $\sim 10^{-6}c^2$. Most of the power emerges in the sub mm part of the spectrum. The X-ray emission appears to be rapidly variable with large flares developing on timescales less than an hour. The X-ray spectrum is steep and presumably nonthermal implying an upper limit on the density of gas close to the hole. The large linear polarization at wavelengths $\lesssim 1$ mm

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are similarly indicative that the density is low. These observations are strongly suggestive that the rate of mass accretion onto the hole is much less than the rate of supply, implying that most of the supplied mass is driven off in a wind, powered by the small fraction that accretes onto the hole.This is entirely natural as the torque that transports angular momentum outward in an accreting flow also transports energy so as to unbind an adiabatic flow. Provided that there is a either a means of creating entropy at the disk surface, as happens in the solar wind, or large scale magnetic fields are present (as is also true of the solar wind), then outflows are to be expected.

Similar outflows are to be expected in the high mass accretion rate case and these are presumably responsible for the observed broad absorption lines that are observed from many quasars. These principles should also apply to accretion onto Galactic black holes, for example GRS 1915+115 (*e.g.* Mirabel & Rodriguez 2002).

7. Ultrarelativistic Outflows

The most dramatic phenomena that are observed in high energy astrophysics are associated with the highest energy particles and the most nonthermal spectra. These, in turn, have been associated with ultrarelativistic outflows. I would now like to be provocative and suggest that we may have been seriously misinterpreting most of these flows at least in recent years and that much older interpretations may have been much closer to the truth (*cf.* Blandford 2002).

7.1. Pulsar Wind Nebulae

Let me start with pulsar wind nebulae, like the Crab Nebula. These are powered by central, spinning, magnetized neutron stars and there is no dispute that the mechanical spin energy of the star is steadily converted into an electromagnetic Poynting flux that carries energy into the magnetosphere. To order of magnitude we can associate a flux $\Phi \sim 10^{14}$ Wb with the open field lines of a typical pulsar and if the angular frequency is $\Omega \sim 100$ rad s^{-1}, the induced EMF is $V \sim \Omega\Phi \sim 10^{16}$ V. We can think of this driving a current flow through the magnetosphere. Under electromagnetic conditions, the "load" in the circuit will be $Z \sim 100\ \Omega$, and therefore the current will be $I \sim V/Z \sim 10^{14}$ A. The power dissipated in the load — essentially the pulsar luminosity — is $L \sim VI \sim 1^{30}$ W.

Where is this load located? The conventional view is that this electromagnetic energy flux is somehow converted into a particle energy flux, perhaps in the vicinity of the light cylinder and probably comprising electron-positron pairs. This is the location of the load. The Lorentz factor of the wind speed has been estimated to be as high as $\sim 10^6$. This fluid outflow is then supposed to pass through a strong shock where its momentum flux matches the ambient nebular pressure and where relativistic particles are re-accelerated.and, perhaps, magnetic field is regenerated.

However, what is seen in the recent X-ray observations of pulsar wind nebulae is very surprising. Polar jets are quite common (*e.g.* Helfand 2001) and the ring-like structures that are observed appear to be confined to the equatorial plane. (It is tempting to associate the moving, ring-like features, especially in the Vela supernova remnant, with large glitch activity as occurs roughly once

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per two years.) This tells us that accretion disks are not necessary to create a jet morphology. It also tells us that if there really are fluid outflows that energize the ray emission, then these are concentrated at the poles and in the equatorial plane.

What I think these observations are, instead, telling us is that the current does not dissipate near the light cylinder but flows out into the nebula. There are relatively strong arguments that suggest that large amplitude waves with periods equal to the rotation period will become nonlinear and unstable and therefore it is simplest to assume that the currents well beyond the light cylinder are primarily conduction currents. However, this is not required.

We then have a picture of a pulsar wind nebula as a giant electrical circuit with current flowing out (in) along the poles and in (out) in the equator. The current completes at the slowly expanding surface of the nebula where there is a contact discontinuity against the shocked interstellar medium. Associated with these currents is a magnetic field that is ' largely toroidal that can be thought of as spun off by the central star. The energy flow in the nebula is given by the Poynting flux, $\vec{E} \times \vec{B}$. The electric field distribution is basically poloidal and derives from space charge distributed along with the currents. If the pressure and the inertia of the plasma in the nebula can be ignored, and this is the appropriate approximation to make under electromagnetic conditions,then the electromagnetic field will be force-free *i.e.* $\rho\vec{E} + \vec{j} \times \vec{B} = 0$. The electromagnetic setup can be much more complex than this simple model. There will probably be currents and space charge flowing throughout the nebula and the pressure and inertia of the plasma in the nebula may well be important, but the simple model is sufficient to fix ideas.can be ignored.

Such a configuration is generically unstable (just like fluid jets). Typically, pinches, kinks and, especially, helices develop around line currents in plasmas. Likewise, sheet currents, like those in the equatorial plane, are subject to tearing mode instability. Usually, this is regarded as a fatal defect for a model. However, I would argue that it is an attractive feature of the present proposal. This is because it is possible that the nonlinear development of these instablities is responsible for the electrical resistance in the circuit and for the X-ray emission that is observed along the poles and in the equatorial plane. (Note that the source of the power that is dissipated in this manner is the magnetic energy stored in the nebula; it does not flow along the jet, but as Poynting flux from the body of the nebula to where the current flows.) One possible way that this can happen is that the macroscopic instability drives a wave turbulence cascade that ultimately is dissipated at some inner scale through the acceleration of relativistic electrons.

There are a variety of predictions associated with this model. The two most direct are that the if the electrons are accelerated close to the currents, then there should be spectral evidenced for aging as the particles diffuse away from the putative acceleration sites.Secondly the linear polarization ought to reflect the underlying magnetic field geometry.

7.2. AGN Jets

The X-ray images of extragalactic (and also Galactic) jets are no less striking.and present a similar choice. It now seems to be generally accepted that jet power

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derives from electro-/hydromagnetic stress applied on the black hole spacetime and the gas that orbits it. The details are just as contentious as with pulsars. In round numbers, a powerful radio source, like Cygnus A, will generate an EMF $V \sim 300$ EV, a current $I \sim 3$ EA and a power $L \sim 10^{39}$ W. Again, it is commonly presumed that the circuit closes to the black hole and a fluid jet is collimated and launched. (Observations of M87 suggest that the collimation happens within $\sim 100m$, Junor, Biretta & Livio 1999.) The various features that are seen using VLBI in the compact, relativistic jets are usually identified with internal shocks — the nonlinear development of velocity gradients associated with either the source or instabilities (*e.g.* Blandford & Königl 1979). Their measured, outward, superluminal motion is then that of a shock front and the Doppler beaming is that of the downstream flow, which moves more slowly than the shock front.

The jets themselves are impressively well-collimated. Even more remarkable is the discovery that they are X-ray bright along their length. In the case of sources like M87, it is argued that X-rays are due to synchrotron radiation. This imples that the particle acceleration must be occuring all the way along the jet's length because the cooling times of the $\gtrsim 10$ TeV electrons are very short. This, in turn, implies that the acceleration cannot occur at internal shocks because strong shocks must be separated by much more than the synchrotron cooling lengths.

By contrast, if we adopt the electromagnetic model, the "jets" delineate the current which flows all the way along the jet to the hot spots and then back to the central black hole mostly along the periphery of the source. The extended radio lobes contain a reservoir of magnetic energy that can supply the emitting regions with energy in addition to the Poynting flux of energy flowing along the jet. (It is helpful to think of magnetic energy as moving with a speed equal to $\vec{E} \times \vec{B}/B^2$ which can be arbitrarily close to c. Disturbances can therefore be observed moving with apparent superluminal speed just like the disturbances in fluid jets.) Continuous X-ray emission along the jet causes no problem because the current is continuous and ohmic dissipation / particle acceleration can occur all the way along it.

7.3. Gamma Ray Bursters

Finally, consider, Gamma Ray Bursters (GRBs) (*e.g.* Mészáros 2002). These come in two basic types with short and long duration. Only the latter class has been well-studied. Several "long" bursts have been associated with afterglows that have been observed from radio frequencies to X-ray energies. Many of the models of gamma ray bursts basically involve some form of electromagnetic induction. A field of ~ 100 GT associated with a rapidly spinning stellar mass black hole or neutron star can induce an EMF $V \sim 30$ ZV and a power $\sim 10^{43}$ W. The source is typically active for ~ 100 s so the total energy of the burst is $\sim 10^{45}$ J. Observations of achromatic breaks in the afterglow light curves have been used to argue that the explosion is not isotropic but instead beamed within a solid angle, typically ~ 0.1 sterad. In other words, GRBs are relativistic jets too.

The conventional view of GRBs is, once again, that the Poynting flux is quickly and continuously transformed into a radiation-dominated fluid with a

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high entropy per baryon, typically $\sim 10^6 k$. This "fireball" (Cavallo & Rees 1078) is collimated into a pair of anti-parallel jets, perhaps within a collapsing massive star. As the flow accelerates along these jets, the internal energy contained in the radiation and pairs is transformed into the kinetic energy of the protons and by the time the photons can escape, the ions are moving with Lorentz factors $\Gamma \sim 300$. Small velocity gradients, induced at the source, steepen into internal shocks at a radius $\sim 10^{11}$ m and γ-rays are emitted as synchrotron radiation. Most of the afterglow emission is formed at radii $\sim 10^{15-16}$ m at the external shock that precedes the spreading, decelerating jet.

However, if the energy is released electromagnetically, it is quite hard to understand how entropy can be created so quickly. The potential differences are so large that the vacuum is, in effect, a perfect conductor so that the invariant $\vec{E} \cdot \vec{B} = 0$. If the other invariant $c^2B^2 - E^2$ is negative, then it will be possible to transform into a frame where there is a pure electric field which will instantly discharge; if it is positive, there will exist frames with a pure magnetostatic field, where nothing will happen. The problem is essentially the same as that of the pulsar wind and I argue that it is quite reasonable that the escaping power be predominately electromagnetic.

There is a second, serious concern with the fireball model. High Lorentz factors are necessary in the jet in order to avoid pair production by the escaping γ-rays. However, these high Lorentz factors are equivalent to high Mach numbers ($M \gtrsim 300$) and it is very hard to see how these can be formed naturally and be sustained while, at the same time, dissipating much of their kinetic energy through internal shocks.

The electromagnetic model of GRBs posits that the energy remain in low entropy, electromagnetic form all the way out to the γ-ray emission region which can be located around $\sim 10^{14}$ m. The flow is no more than mildly supersonic, depending upon the plasma loading. By the time this radius is reached, the electromagnetic field will be confined to a thin, relativistically expanding shell, pushing a blast wave out into the surrounding medium. Instabiliites in this shell will ultimately be responsible for the particle acceleration and the GRB.

Whatever one's view of the relative merits of fluid and electromagnetic models of ultrarelativistic outflows, and perhaps the truth lies between the two extremes described above, it is clear that there is a convergence in the study of pulsar wind nebulae, AGN/XRB jets and GRBs.

8. Physics at the Frontier

High energy astrophysics is a young and relatively immature field. It owns much of the remaining unexplored "discovery space" in contemporary astronomy. Two examples of this discovery space are the extremes of observation of the electromagnetic spectrum. At the high end, there are already about ten TeV sources, while at the low end of $\lesssim 50$ MHz radio astronomy there are essentially no sources. Neutrino astronomy claims only two cosmic sources so far, the sun and SN1987a. Even the venerable field of cosmic ray physics may be on the threshold of becoming cosmic ray astronomy. Finally, as many of the most interesting high energy sources are ultimately black holes and neutron stars, the exciting field of gravitational wave astronomy — perhaps a decade away

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from birth — is inextricably linked to high energy astrophysics. These are the frontiers and I consider them in turn.

Atmospheric Cerenkov techniques are being used to detect γ-rays in the GeV–TeV range. These are important as both sources and as probes. Persistent sources have been identified with pulsars, blazars and supernova remnants and in each case are likely to provide the best approach we have to understanding the fundamental nature of these sources. The big issue in pulsars is to locate the source of the emission. Is it close to the stellar surface or at an outer gap, much closer to the light cylinder? As the pulses are phase-resolved, we can also relate the γ-ray emission site to that of the radio, optical and the X-ray emission which is also not yet certain. Blazars are identified with ultrarelativistic jets emanating from massive black holes in the nuclei of elliptical galaxies. Here the big question is to understand whether the jets comprise ultrarelativistic protons, that interact with either the radiation field or the background plasma, or if they are electron-positron pairs/electromagnetic. TeV sources should be far more plentiful in the latter case. The combination of GLAST and telesopes like Hess and VERITAS ought to be able to sort this out, as they should also be able to sort out the details of cosmic ray acceleration in supernova remnants, as discussed above.

At the other end of the spectrum lies the domain of low frequency radio astronomy (Kassim & Weiler 1990). The ionosphere precludes regular observing much below $\sim$ 30 MHz and it is necessary to fly large antennae in space to explore this part of the spectrum. We can be confident that the sources exist. They are necessarily nonthermal. The ultimate limit in frequency is the plasma frequency of the solar wind, around $\sim$ 30 kHz, giving us another ten octaves to explore. There will of course be limitations. Interstellar propagation will lead to irreversible smearing of any pulsar pulses, for example.

The great advantage of neutrino astronomy is that allows one to see into the densest regions, even through nuclear density. The recent successes in the SNO and Kamionkande and KamLAND experiments have verified that the three types of neutrino have mass and can mix into each other. This vindicates the standard solar model although the low energy neutrino spectrum remains to be measured.

The next step in neutrino astronomy is to detect sources at much higher energy. This is the province of projects like AMANDA, IceCube and ANTARES. The prime candidate sources of ultra high energy neutrinos are blazars and GRBs. In many respects, these searches are complementary to the UHE γ-ray searches. Success in the former will suggest that ultrarelativistic outflows comprise mainly protons. Failure, and there is no guarantee that there will be *any* detectable UHE neutrino sources, will favor electromagnetic/pair models UHE. neutrino astronomy has the advantage that we can see the universe up to $\sim$ EeV energies. By contrast, the universe becomes opaque to γ-rays above $\sim$ TeV energies through absorption by the infrared background.

The cosmic ray frontier is undoubtedly at the very highest energy. The situation is now quite confused. The EeV cosmic ray spectrum can be measured through detecting the atmospheric nitrogen fluorescence that they create and by recording the muon showers on the ground. Unfortunately different spectra are being reported — probably a consequence of calibration errors. What is at stake is the source redshift. If the cosmic rays derive from cosmological distances, then

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they should cut off above ~ 100 EeV due to photopion production by the cosmic microwave background. If this "GZK" cutoff is not seen then their sources probably lie within ~ 30 Mpc and their overall mean luminosity density approaches that of ~ GeV cosmic rays. Even more tantalizing are studies of the angular distribution of these particles. There are a few close groupings of particles — five doubles and one triple — on the sky. The statistical significance is low, but if these are substantiated as permanent sources, then almost all proposed models of UHE cosmic ray origin will be ruled out, with the conspicuous exception of the front runner, radio sources associated with dormant massive black holes in AGN. Both of these questions should be answered by Auger.

Finally the last and most challenging frontier is that of gravitational radiation. Studies of binary pulsars have confirmed that the weak field calculations of wave emission are correct to an accuracy ~ 0.002. This is the most impressive confirmation of the general theory of relativity to date. This allows us to compute waveforms etc from strong field sources, according to the rules of general relativity with confidence, although not facility. However, it does not rule out the possibility that additional fields are attached to singularities, for example, or that the relationship between curvature and stress-energy is more subtle. Furthermore, it is at least logically possible that in a universe where this relationship *appears* to fail on the comsological scale, there could be some side effects affecting the propagation of metric perturbations. In short there are pretty good reasons in physics to test the theory of gravitational radiation although the most likely outcome will be to vindicate, once again, the genius of Albert Einstein.

Gravitational radiation astronomy is largely unkown territory. There are however assured sources - Galactic binary dwarfs and extragalactic neutron star coalescences. Of more interest, though, are coalescing black holes in cosmologically distant galactic nuclei, though here the source rates are very difficult to estimate with confidence and measuring them would tell us much of interest about galaxy evolution. There are two classes of detectors. Ground-based facilities, like LIGO, TAMA and VIRGO, will seek stellar sources like supernova and compact object mergers. mHZ, space-based facilities, such as LISA, will target massive black hole signals from behind a binary white dwarf-generated foreground. The technical challenge of achieving the sensitivities necessary to measure waves from assured sources should not be understated. It may well take more than another decade to reach them. However, there have been few regions of the electromagnetic spectrum where the sources have turned out to be as we imagined. So, it would be remarkable if gravitational wave astronomy, or any of the other four frontiers turned out to be as I have just described.

As I hope that this brief introductory essay makes clear, the past decade has been a remarkable one in the observation of high energy astrophysics. The present one promises even more. Let me conclude by re-emphasizing the two important principles with which I began this article. Firstly, in order to exploit high energy observations to the full it is necessary to adopt a source-based, rather than observatory-based approach to the study of cosmic sources. Almost by definition, high energy sources are nonthermal and emit throughout the electromagnetic and other spectra and spectrally chauvinist interpretations of their behavior are incomplete. Secondly, much of the physics of these sources

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is unknowable working from first principles. While we should be confident in our application of fundamental principles, such as the conservation laws of mass momentum and energy and the whole edifice of general relativity, and in our understanding of elementary processes such as those described by atomic and nuclear astrophysics and quantum electrodynamics, much of what we see depends upon the collective behavior of plasmas and the mysteries of MHD. As such, it is encumbent upon us to develop theories of these subjects by studying all sources from the solar corona to GRBs so as to derive empirical laws which we can then try to relate to numerical simulation. The physics should be common and knowable.

I am confident that subsequent contributions to this meeting will report great advances that can be interpreted in terms of both of these principles.

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