Recent X-ray observations have had a major impact on topics ranging from protostars to cosmology. They have also drawn attention to important and general physical processes that currently limit our understanding of thermal and nonthermal X-ray sources. These include unmeasured atomic astrophysics data (wavelengths, oscillator strengths etc.), basic hydromagnetic processes (e.g. shock structure, reconnection), plasma processes (such as electron-ion equipartition and heat conduction) and radiative transfer (in disks and accretion columns). Progress on these problems will probably come from integrative studies that draw upon observations, throughout the electromagnetic spectrum, of different classes of source. X-ray observations are also giving a new perspective on astronomical subjects, like the nature of galactic nuclei and the evolution of stellar populations. They are contributing to answering central cosmological questions including the measurement of the matter content of the universe, understanding its overall luminosity density, describing its chemical evolution and locating the first luminous objects. X-ray astronomy has a healthy future with several international space missions under construction and in development.

Keywords: X-rays, accretion, black holes, galaxies, cosmology

1. Introduction

Out of the nearly seventy octaves of electromagnetic spectrum that have been opened up to astronomical observation, X-ray astronomers can lay claim to roughly ten (as opposed to the single octave explored by optical astronomers!). Although no one would pretend that all octaves are equally interesting in terms of physics, there are some special reasons why the X-ray band is peculiarly informative. It includes the K- and L-shell transitions of all the post-big bang elements. It is where to find thermal emission from gas with sound speed $\gtrsim 300 \text{ km s}^{-1}$, typical of the intergalactic medium, galaxies and stars. It lies right below $\sim m_c c^2$, which is a characteristic energy scale for many nonthermal processes.

X-ray astronomy began forty years ago with the discovery of Sco X-1 [Giacconi et al. 1962, Pound] and was enthusiastically developed surprisingly soon after the dawn of the space age, perhaps because radio astronomy had, by this time, revealed a universe of sources with strength and properties that were completely unexpected on the basis of optical observations. By the time Sco X-1 was identified, quasars and the microwave background had been discovered and pulsars were soon to follow. These four discoveries ushered in modern astronomy.
As this Discussion Meeting celebrates, X-ray astronomy has come a long way. It is, arguably, ceasing to exist as a separate observational subfield of astronomy, so central have X-ray observations become to the study of essentially all classes of cosmic sources. The most improbable objects – brown dwarfs, all types of protostar and the moon for example – have been detected in X-rays [Güdel]. However, in spite of the fascination of this history, it is to the present and the future that we must turn and earlier speakers have taken stock of where we are after a couple of years of full operation of Chandra and XMM-Newton and what the prospects are for the future. Even this has turned out to be too ambitious to cover in a two day meeting and the papers presented here (and a fortiori this brief summary) have had to be quite selective and I shall defer to the other contributors for more representative bibliographies.

As the only non-observer speaking at this meeting, I have organized my commentary around three themes that are somewhat “orthogonal” to the preceding, source-centered talks. These are the physical processes that are ultimately responsible for X-ray emission, the peculiar importance of X-ray observations in rounding out our view of the structure and evolution of stars and galaxies and the under-acknowledged role of X-ray astronomy in defining the cosmological world model to which we have been led in recent years and which is now starting to raise some very important questions concerning what actually happened in the first Gyr of the life of the universe. I conclude with a brief listing of the proposed next generation of X-ray observatories.

2. Physical Processes

The description of many high temperature and nonthermal sources is dependent upon some poorly understood physical processes. It is striking how often the same questions are asked of quite different physical environments. How important is thermal conduction? How effective is magnetic reconnection in heating plasma? And so on. The optimistic view, that links several of the talks, is that we really only have to solve these problems, e.g. the structure of Mach 30 shocks, once and we should be prepared to combine astrophysical, space physical observational with laboratory experiments and computational work to develop some confident answers.

(a) Spectroscopy and its Interpretation

The gratings on XMM-Newton and Chandra have unprecedented spectroscopic capability, and the ability to utilise them so effectively has benefitted from over thirty years of hard (and largely unacknowledged) work measuring and computing wavelengths, oscillator strengths and so on for transitions of little terrestrial interest. Of particular importance are the Helium-like triplets which combine observations of permitted, intercombination and forbidden transitions (Gabriel & Jordan 1969, [Kahn]) so as to provide density and temperature diagnostics. The low densities that allow forbidden transitions to be so important in cosmic sources are hard to work with experimentally. Conversely, the high radiation densities that allow radiative ionisation equilibria to be established are only just being achieved using powerful lasers.

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By now, most of the important wavelengths, oscillator strengths, collision integrals etc. for the strongest lines have been measured, although these measurements are still lacking for the majority of the weaker lines that can also be observed in the brightest sources. Observations of H-like and He-like transitions of the more common ions provide useful diagnostics of the density, temperature, abundance, ionization equilibrium and velocity in the emission regions and we have seen here many examples of what can be done in a wide variety of sources including accretion disks (stellar [Done] and AGN [Fabian]), stars and protostars [Güdel], clusters of galaxies [Mushotzky] and polars [Cropper]. The power of X-ray spectroscopy is most clearly brought out by the detailed observations of bright supernova remnants [Canizares]. Here, it is possible to use the $\sim 100 \text{ km s}^{-1}$ velocity resolution to make three dimensional abundance maps of the expanding debris and forensic analyses of the initial explosions.

Unfortunately, most other sources are unresolved and most direct analyses of the data are often limited to one zone models and some very primitive radiative transfer. Now, it is possible, at least in principle, to include anisotropy, inhomogeneity and peculiar geometric effects in theoretical models of these sources. The problem is that we really have no clear idea of the disposition and structure of the emission region and the medium through which the radiation is propagating. A particularly important example is provided by the ongoing debate concerning the soft X-ray spectra of Seyfert galaxies. Does the power-law, continuum source that is reflected by the disk arise in a local corona or at high altitude so that it can illuminate the whole disk? Are the carbon and oxygen lines produced by reflection (Sako et al. 2002) or in a dusty, warm absorber (Lee et al. 2001) again at some distance? Why does there appear to be no sign of a reverberative response in Seyfert galaxies with variable X-ray continua? Answering these questions using a more detailed analysis of line formation in the two cases, is tantamount to understanding the source geometry. However, as broad emission lines are now being reported from binary X-ray sources like Cyg X-1 [Fabian] and J1650-500 (Miller et al. 2002), it is reasonable to suppose a model that works for Seyferts should also work for black hole binaries.

A second example is provided by stellar coronae, where hot, coronal gas is excited by twisted, magnetic loops. (Temperatures as high as 40 million degrees are now reported associated with the Galactic Cepheid, YY Mon [Güdel] .) Although we can image similar activity in the sun, we still do not understand it at all well. Again, we do not have an agreed story as to the sequence of events that leads to coronal lines being emitted and, consequently, how to convert raw line strengths from distant stars into physical conditions in their coronae. The observation of coronal activity from late M stars that are thought to be cool enough not to possess surface convection zones suggests that other, non-magnetic processes could be at work. Again, there is probably a general theory that can be inferred by combining solar and stellar observations.

A third case, where we probably do understand the geometry and can compute the emissivity and opacity, is provided by cyclotron line formation in accreting white dwarfs [Cropper]. Although eclipse observations have confirmed the expected strongly inverted temperature gradient, the radiative transfer is quite subtle and a far more detailed theoretical treatment is likely to be necessary for us to reproduce the observed spectra as well as their polarisation and time-dependence. (Monte
Carlo techniques will surely continue to play a major role here and some of the 
experience gained from working with Tokamak plasmas may be relevant.)

\[(b)\] The Plasma Impasse

X-ray sources are, inevitably, fully ionized gases. It is therefore unfortunate that 
X-ray astronomers have been resistant to learning the principles of plasma physics 
and incorporating them into their science, preferring instead to limit their purview 
to gas dynamics and atomic physics. This evasion can no longer be excused. There 
are now several sources where progress awaits the answers to fundamental plasma 
physics questions. Again, I only have space for a few examples.

The first question is “How fast do ions with some temperature \(T\) heat cooler 
electrons?” There is a minimal and standard heating rate resulting from two body 
Coulomb scattering. However, there is an abundance of wave-particle interactions 
that might, for example, be excited by streams of fast particles. The empirical 
evidence comes from the observations of high Mach number, heliospheric and su-
pernova remnants shock fronts, which appear to transmit thermal electrons with 
a temperature well below the equipartition value so that the ions do not quickly 
attain collisional ionization equilibrium [Canizares]. This suggests that collective 
effects are not that important. This view is supported by observations of slowly ac-
creting black holes which are also best interpreted in terms of a minimal, Coulomb 
heating rate. The answer to this question is of direct relevance to the debate about 
the efficacy of electron heat conduction. There are really two issues. What is the 
mean free path of the electrons along the magnetic field and how quickly do the 
field lines wander in response to an imposed turbulence spectrum? As discussed 
below, our best laboratories are clusters of galaxies.

A related plasma question concerns the efficiency of strong shocks for acceler-
ating cosmic rays. There is a linear theory which appears to have some validity, 
again based upon heliospheric measurements and X-ray observations of supernova 
remnants [Canizares]. However, in order to model the observations, we have to 
understand how the back reaction associated with the cosmic ray pressure moder-
ates the acceleration and what controls the rate of both ion and electron injection. 
Theoretically, it may soon be possible to perform \(3 + 3\) dimensional kinetic simula-
tions with sufficient resolution to address these questions. Observationally, GLAST 
should provide measurements of the energetically-dominant GeV ions. As relativis-
tic electrons are scattered by the same Alfvénic turbulence that operates on the 
ions, the combination of \(\gamma\)-ray and X-ray observations should enable us to infer the 
injection rate and perhaps determine the scaling with Mach number.

Another, quite controversial feature of shock fronts is their role in amplifying 
magnetic field. Theoretically, there is no very good reason why simple gas dynamical 
shocks should do any more than compress the pre-shock magnetic field. In addition, 
radio observations of many (though not all) supernova remnants seem to show that 
the emissivity and, presumably, the magnetic field strength only increase in the in-
teraction region between the shocked ejecta and the swept up interstellar medium. 
Conversely, it is possible that the hydromagnetic turbulence that is invoked to scat-
ter the cosmic rays leads to an overall increase in the rms magnetic field strength. 
This is highly relevant to the late-time evolution of \(\gamma\)-ray burst afterglows.

Even greater uncertainty surrounds our understanding of relativistic shocks,
which are thought to be the primary acceleration site for X-ray-emitting relativistic electrons and magnetic field amplification in γ-ray bursts, pulsar wind nebulae and extragalactic jets. However, the diffusive mechanism for particle acceleration that operates nonrelativistically is kinematically precluded. There is a promising relativistic variant (Achterberg et al. 2001). However, this assumes that the cosmic rays can move far enough upstream from the shock to scatter off the background flow and it is not clear how this can happen if there is an oblique magnetic field. Neither is it clear how the scatterers can be generated. The magnetic field itself is also believed to be strongly magnified at the shock front, though no good explanation of how this happens has been found. Indeed, the very existence of sudden, collisionless discontinuities, as opposed to a slow sharing of momentum between two fluids, has been questioned. X-ray observations should be especially instructive because they permit us to resolve these putative shocks, say in the Crab Nebula and jets like M87, at energies where the emitting, relativistic electrons quickly cool. The observation of what is presumably X-ray synchrotron radiation well away from the supposed strong shocks implies that relativistic electrons have to be accelerated in situ, rather than at strong shocks. These observations further raise the possibility, discussed elsewhere, (Blandford 2002) that the observed sources including their “shocks” are actually relativistic, electromagnetic structures and are not well-described by gas dynamics.

Another general process is magnetic reconnection which has been invoked, for example, in explaining the energisation of accretion disk coronae. However, the manner in which it operates remains quite controversial. Most existing discussions (e.g. Priest & Forbes 2000) have been essentially hydromagnetic except within a small region where the magnitude of the field gradient becomes very large and where a scalar (and usually “anomalous”) resistivity is invoked. A recent development, which has serious implications for the topological behaviour, is that the resistivity might be dominated by non-dissipative, Hall terms (Bhattarcharjee, Ma & Wang 2001). These embellishments of MHD are now finding their way into numerical simulations and it will be interesting to see what are their implications for X-ray sources.

In addition to numerical simulation and in situ observation of space plasmas, it is becoming possible to address some of these questions using the growing field of laboratory experimentation. It is now possible to create relativistic plasmas - both ionic and pair plasmas - using powerful lasers, electron beams and magnetic pinches. Temperatures as high as 100 MeV, energy fluxes of $\sim 100 \text{ ZW m}^{-2}$ and $\sim 1 \text{ MT}$ magnetic field strengths are all attainable. “High energy density” investigations are likely to become much more versatile in the coming years (e.g. Takabe 2001).

(c) Black Hole Accretion

The problem of accretion onto a compact object, specifically a black hole, is generally well-posed but has also not had a confident solution over the past thirty years. However, through a combination of theoretical arguments and direct observation of accreting sources, it has been possible to make a lot of progress recently. The greatest excitement has probably centred around the occasional observation of broad iron lines from selected, low luminosity AGN and, as reported here, a couple of Galactic binary X-ray sources [Fabian, Done]. (We now know that broad
lines are not seen as commonly as once thought and that their formation must be more complicated than envisaged in early models. The prospects for performing useful “reverberation mapping” do not look good.) In those sources, where these features are undoubtedly seen, we can say that there is evidence that the second parameter that characterizes a classical black hole – the spin – is responsible for the line width. Indeed, it has even been argued that the role of the black hole is not just the passive one of allowing stable orbits from which highly redshifted photons can be observed, but is an active one in which a magnetic connection of the gas to the spinning hole leads to an enhanced emissivity from the innermost, and most redshifted orbits (Wilms et al. 2002).

Another very promising line of investigation is epitomized by the observations of Sgr A* which show that the black hole is a strikingly underluminous X-ray source with an apparent luminosity $\sim 10^{-8} \, L_{\text{Edd}}$ and a radiative efficiency of $\sim 10^{-7} c^2$ relative to the inferred mass accretion rate of $\sim 10^{22} \, g \, s^{-1}$. There have been several explanations put forward, but most of these require that the rate of electron-ion equilibration be slow, as discussed above. It no longer seems possible that all of the mass supplied can accrete onto the hole and either most of the mass is lost (Blandford & Begelman 1999) or the accretion backs up to the Bondi radius at $\sim 10^7$ gravitational radii. The whole matter has been made more interesting through the discovery of surprisingly rapid X-ray variability in Sgr A* (Baganoff et al. 2001) and the even more remarkable suggestion that the radio variation may be periodic (Zhao, Bowers & Goss 2001). These observations open up many more possibilities and will undoubtedly be quite constraining once the observational situation is clarified.

Galactic black holes provide more immediate gratification for observers than massive black holes, both on account of their larger fluxes and also because of their much more rapid variability timescales [Done]. There is now a fairly convincing, qualitative explanation of the low and high states. The former arise when the luminosity is $\gtrsim 0.03 L_{\text{Edd}}$ and a thin (or slender) disk extends down to $r_{\text{ms}}$; the latter when there is a central hole filled by gas that cannot cool and radiate efficiently and where a nonthermal spectrum is created by Comptonisation. It is not clear that all of this gas accretes onto the black hole.

Many of the questions raised by these observations are issues of theoretical principle that are still being debated. The approaches that will be necessary to address these questions are both observational and theoretical. For the former, the angular resolution of Chandra can be put to great advantage resolving the accretion radii in nearby, dormant galactic nuclei. These observations are helping us to define the physical conditions and perhaps to deduce the rate of gas supply to the central black hole. Theoretically, there are opportunities for carrying out 3D numerical fluid dynamical and MHD/electromagnetic (including general relativistic) simulations of disks and outflows.

(d) Nonthermal Emission

The capability to perform arcsecond imaging at X-ray wavelengths is revolutionizing our view of nonthermal emission. Surely, the most famous instance of this is the discovery of a pair of axial jets in the Crab Nebula (Weisskopf et al. 2000) as well as other Pulsar Wind Nebulae. This was relatively unexpected and shows
that accretion disks are not necessary for “jet” formation. However, it may suggest something even more fundamental and to explain this, I should return to one of the first models of a pulsar, the Goldreich-Julian, axisymmetric model. Here, it was proposed that a spinning, magnetised neutron star acts as a unipolar inductor and generates an EMF, $\mathcal{E} \sim 30$ PV in the case of the Crab pulsar and that this drives a current $\sim 300$ TA around a quadrupolar circuit. (We now know, thanks to Ulysses, that the heliospheric electrical circuit is of this form although the EMF and current are only $\sim 100$ MV and $\sim 1$ GA respectively.)

Now real pulsars are, by definition, non-axisymmetric and the electromagnetic field just beyond the light cylinder will contain both an AC and a DC component. The interaction between these two components is unclear, but it has generally been assumed that essentially all of the electromagnetic Poynting flux is quickly converted into the kinetic energy of a plasma-dominated, outflowing wind. In other words, the electrical circuit is completed quite close to the pulsar. In this case, a hypersonic wind is created which, it has been supposed, passes through a strong shock front with Lorentz factor $\sim 10^6$ close to the famous “wisps”, where particle acceleration and nonthermal emission can occur. However, the X-ray image really shows no evidence for this shock front except perhaps along the poles and the equator. The moving features that are seen optically also appear to be confined to the equatorial plane.

These observations suggest a different interpretation (Blandford 2002), specifically that the AC electromagnetic component dies away very quickly, perhaps non-dissipatively while the DC component persists all the way into the nebula. In this case, the X-ray emission that is observed largely delineates the quadrupolar current flow. More specifically, there is no strong, reverse shock and relatively little of the current completes close to the pulsar. The emission that is seen may well reflect MHD instability in the magnetic configuration - pinches and current sheets are notoriously unstable - and be a manifestation of ohmic dissipation. In this case, the observed Crab Nebula would be magnetically-, rather than particle-dominated except, perhaps, in the emission region where the relativistic electron energy density might build up to an equipartition value. These ideas should be testable by examining the spectral index gradients and the polarization map.

This viewpoint has implications for ultrarelativistic jets and gamma ray bursts (GRB), which are now also widely acknowledged to have an electromagnetic origin but where it is also supposed that the Poynting flux is quickly converted to fluid form (most commonly as an optically thin pair plasma in the former case and as a radiation-dominated fireball in the latter) and that the ultimate emitters are strong, relativistic shock fronts. By contrast, under the electromagnetic hypothesis, it is supposed that the energy released remains in an electromagnetic form all the way to the emission region and that the particle acceleration is a direct result of wave turbulence. There should be ample potential difference available for particle acceleration to take place. In the case of a quasar jet, the EMF is $\sim 100$ EV and the current is $\sim 1$ EA. (For GRBs the estimates are now $\sim 10$ ZV and $\sim 100$ EA, rather lower than in the past.)
3. Astronomical Questions

(a) Nuclear Power

High angular resolution, X-ray observations have, in an almost literal sense, transformed our view of active galactic nuclei (AGN). They have amply confirmed the finding from optical observations, that our classification of these sources is strongly aspect-dependent. The simple geometrical model of an AGN invokes a thick torus that will absorb UV continuum and emission lines and all but the hardest X-rays and γ-rays and then re-emit the absorbed energy in the thermal infrared. This description has received impressive confirmation with ASCA, XMM and Chandra measurements of hard X-ray spectra [Matt] which clearly exhibit the effects of absorption with hydrogen column densities that can approach \( \sim 10^{24} \text{ cm}^{-2} \). This, in turn, implies that a significant fraction of the infrared background, as well as the bolometric luminosity density of the young universe, be associated with AGN. In round numbers, the energy density associated with the observed X-ray background (mostly in the energy interval \( \sim 20 - 40 \text{ keV} \)) is \( 3 \times 10^{-17} \text{ erg cm}^{-3} \), a fraction \( \sim 0.003 \) of the energy density measured in both the optical and in the far infrared backgrounds (and \( \sim 10^{-4} \) of the microwave background energy density). In other words, if the intrinsic, integrated, UVX power of an AGN is, on average, thirty times the HX power and this is a reasonable guess based upon observations of local AGN, then AGN must account for \( \sim 10 \) percent of the infrared background, with the remainder being presumably associated with stars. Estimates in the literature based upon more detailed assumptions about the mean AGN spectrum and the redshift distribution of the sources range from \( \sim 3 - 30 \) percent. However, this quantity may not be very well-defined because much of the luminosity associated with galactic nuclei could be attributed to starbursts as opposed to accretion onto massive black holes [Ward].

The characterisation of the obscuring material as a torus is problematic, at least from a theoretical viewpoint. The difficulty is that it is very hard to see how a thick, cold ring of molecular gas can be supported. Individual clouds should collide inelastically and a torus would quickly deflate. A more plausible alternative (eg Sanders et al. 1989) is that there is a locally thin, though strongly warped disk, where the thickness is maintained through the marginal growth of gravitational instabilities. However there is still confusion about the size of this disk. Combined X-ray and SIRTF observations should greatly improve our understanding of AGN obscuration.

Obscuration is not the only way to produce beaming. The X-ray study of relativistic jets, especially in blazars and nearby sources like M87 (which would probably be classified as a blazar were it pointed at us) is becoming more sophisticated. However we are still not yet able to answer the quantitative questions about beaming fraction, the angular and radial variation of jet Lorentz factors etc. These questions will undoubtedly be a focus of future X-ray research, especially after GLAST is launched.

The luminosity of galactic nuclei is not exclusively radiative. There are “super-winds” which are driven by nuclear activity [Ward]. In addition, roughly ten percent of optically-selected quasars exhibit (X-ray quiet) broad absorption line outflows. Even if these flows only represent a minor fraction of the nuclear power budget, they can still have a large impact on the host galaxies because the momentum flux
of a wind scales inversely with the outflow speed. Not only can these outflows drive away much of the interstellar medium, they may even influence the overall galaxy morphology by, for example, inhibiting or limiting disk formation.

(b) Stellar Populations

X-ray observations are also presenting us with a complementary perspective to that obtained using optical and infrared observations on how the stellar populations of galaxies evolve. This is because they allow us to witness the endpoints of stellar evolution as opposed to the beginnings. So far most attention has been on nearby galaxies, both spirals and ellipticals [Ward]. The primary targets are young supernova remnants and binary X-ray sources. Comparison with radio and infrared observations is particularly important in the former case as it allows us to derive some useful empirical correlations. As an example of what can be learned in this way, it has been reported that the star formation rate declines less rapidly than the supernova rate [Ward].

Probably the biggest new discovery is the ultraluminous X-ray sources which are now showing up quite regularly in all types of galaxy [Ward]. They are defined by having X-ray luminosity in excess of the Eddington limit for a \( \sim 30 M_\odot \) black hole. They have been associated with intermediate mass black holes, conceivably relics from the Population III era. In this case the fuel supply is a bit of a puzzle. They must either be short-lived binaries or single stars moving slowly through molecular clouds and, consequently, a major constituent of the universe, overall. Alternatively, they could be the long-sought stellar blazars, although here the absence of a radio emission is surprising. A third possibility is that they are normal mass black hole binaries with super-Eddington luminosity which may be physically possible in the highly clumped, radiation-dominated fluid that is expected in the innermost regions of accretion disks orbiting \( \sim 10 M_\odot \) black holes, is responsible. Again, this phase would have to be quite short-lived. The heterogeneity of the observed properties of ultraluminous X-ray sources suggests that more than one of these explanations could be correct.

4. Cosmological Issues

(a) Clusters

X-ray observations continue to be of central importance to the study of rich clusters of galaxies [Allen, Mushotzky]. The most basic information concerns the shape and depth of the gravitational potential well. The various methods that have been used to determine this now seem to be in fairly good agreement. Arguably the most reliable is gravitational lensing - strong in the core and weak in the outer parts - especially when there are reliable source redshifts. As demonstrated here, this technique works well for clusters that appear to be nearly circular and which are dynamically relaxed. The total mass density can then be derived from Poisson’s equation. (The smoothness of the known arcs assures us that the potential is also quite smooth.) It is then possible to use imaging spectroscopy to measure the baryon mass distribution, as roughly 85 percent of this is believed to be in the form of hot gas. (In practice this is carried out by model-fitting rather than an unbiased inversion.) This procedure may be problematic near the center of the cluster but
is far safer in the outer parts of the cluster where most of the mass resides and where we are most likely to sample fairly the cosmological mass distribution. If we are prepared to trust the baryon density derived from the measured deuterium (plus other light elements) abundance and the theory of big bang nucleosynthesis ($\Omega_0 = 0.04$), then we can deduce the contemporary matter fraction of the universe and a value $\Omega_0 = 0.31 \pm 0.03$ was quoted (assuming a Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) [Allen]. This argument, which preceded the more publicised type Ia supernova determination and which is less subject to systematic error, appears to be holding up very well. Repeating these measurements with larger redshift clusters, probably in conjunction with Sunyaev-Zel’dovich measurements, should allow us to infer the expansion history of the universe, at least in principle. To date, this translates into an unsurprising bound on $\Omega_\Lambda$.

It is also possible to explore the thermal history of the intergalactic gas by comparing the measured mass – temperature relation with the expectations of adiabatic simulations. It should not be too surprising that the agreement here is less good [Mushotzky, Allen]. The entropy history of the gas which affects this determination is likely to be quite complicated. The gas temperature, immediately after re-ionization by the first stars and quasars is only $\sim 10 \text{ km s}^{-1}$. However as structure grows, this gas will acquire speeds of several hundred km s$^{-1}$. Strong, large scale shock fronts are likely to form and increase the entropy of the gas. However, as noted above, the post-shock electron temperatures will be significantly lower than the ion temperatures (There is no observational evidence for strong accretion shocks surrounding observed clusters; it appears, quite reasonably, that the gas is heated much earlier in the merger hierarchy.) The gas will also be mixed with cooler gas swept out of galaxies. It is very hard to compute the influence of these and other easily-imagined effects from first principles. The dark matter, mass-velocity relation, which is probably best determined by gravitational lensing, is more likely to furnish a robust measure of the growth of large scale structure.

There is an inescapable implication of the cluster gas having been heated by strong shock fronts, whatever their provenance. This is that the hot gas will be accompanied by cosmic ray ions. The speeds and Mach numbers of the shock fronts are quite similar to those in the interplanetary and interstellar media and we expect that the post-shock, GeV cosmic ray partial pressure will lie somewhere in the range 0.2-0.5 of the total pressure. This fraction will decrease slightly as the gas is adiabatically compressed but if the gas starts to cool appreciably then cosmic rays may dominate the pressure and inhibit further cooling. This may be part of the explanation of the suprising results from X-ray spectroscopy by XMM of a few well-studied clusters [Mushotzky]. These seem to show that the gas starts to cool as it flows towards the central cD galaxy and then appears to vanish – the lines expected from gas with temperature below $\sim 2 \text{ keV}$ are absent. By resisting further compression, the cosmic rays will make it easier to keep the gas hot. Other factors that have been invoked to explain the failure to observe cooling flows include variable metallicity, thermal conduction and supernova heating. There is a further implication of having these cosmic rays present and this is that they may contribute to the heating and, in particular, may create $\gamma$-rays through pion production. The predicted $\gamma$-ray flux from nearby clusters should be detectable by GLAST and, under extreme assumptions, could contribute to the $\gamma$-ray background.

X-ray observations are also providing new information on the chemical history of
the universe as we try to reconstruct the history of clusters of galaxies [Mushotzky]. C, N, O, S, Fe, Ni have all been measured in a large sample and abundance gradients in a smaller number. The iron abundance has now stabilized at \([Fe/H] \sim 0.3\) (possibly increasing with the size of the cluster) and is consistent with a Type Ia origin. The supernovae may have occurred mostly in clusters with the processed gas being driven out in superwinds. The correlations of the relative abundances with the cluster properties as well as the radius are starting to become quite diagnostic of the evolutionary history of the cluster gas.

(b) X-ray Background

Another great success for Chandra and XMM-Newton has been the resolution of \(\sim 80-90\) percent of the X-ray background into \(\sim 3 \times 10^8\) discrete sources [Brandt, Hasinger]. As discussed above, most of the energy density appears to derive from black hole accretion in low power AGN. The redshift distribution of these sources is controversial. On the one hand the \(\sim 10^8\) sources which contribute most of the background appear to have modest redshifts \(z < 1\) [Hasinger]; on the other, the faintest sources are seen out to \(z \sim 3\) [Brandt]. In addition, the surveys are so sensitive that nearby normal galaxies and luminous quasars with \(z > \sim 5\) are also found to be minor contributors to the background. I suspect that these statements are approximately true and not in contradiction.

The notion that most of these X-ray sources are obscured receives support from their association with ISO sources and bodes well for SIRTF observations. If, following the example above, we suppose that AGN account for \(\sim 10\) percent of the infrared background then the energy produced, allowing for the expansion of the universe, corresponds to \(\sim 10^7 \, \text{M}_\odot c^2\) per local \(L^*\) galaxy. If we assume that black holes grow with \(\sim 10\) percent radiative efficiency, then we deduce a mean black hole mass per \(L^*\) galaxy of \(\sim 10^8 \, \text{M}_\odot\), roughly compatible with what is measured. In addition, as there are \(\sim 3 \times 10^9\) of these locally-specified \(L^*\) galaxies out to \(z \sim 2\), where most of the black hole mass is grown, we conclude that a typical nucleus of one of these galaxies is active for \(\sim 10^8\) yr, consistent with the Salpeter time.

A possible problem with this neat explanation is that if the spectrum below an observed energy \(\sim 30\) keV really does come from obscured sources, then they must have low redshifts as it is hard to see how an absorption turnover could occur at a much higher energy than \(\sim 40\) keV when scattering dominates any plausible opacity. If this is true, then, when Swift or EXIST identify the sources that contribute most of the hard X-ray background, they should find that they have low redshifts. An alternative possibility is that the hard X-ray sources are mostly at \(z \sim 2-3\) and we are observing hard, Comptonised spectra in a corona with temperature \(\sim 100\) keV. Ultimately, we should like to extend this analysis all the way up to \(\gamma\)-ray energies and make smooth contact with studies of the \(\gamma\)-ray background.

(c) First Light

The famous penetrating power of hard X-rays makes them excellent candidates for probing the very early universe. Recent observations are encouraging. Quasars have been found with \(z \sim 6.5\) and the X-ray powers suggest that the holes exceed a billion solar masses. This is a constraint on theories of the growth of black holes.
and a timely reminder that quasar activity must be intimately related to galaxy formation and evolution during the $\sim 0.5$ Gyr between reionisation and $z \sim 6.5$ when the first quasars are seen. In addition, GRB have already been seen out to $z \sim 4.5$, where the redshift actually helps by allowing an observer with a fixed response time to observe an earlier and brighter part of the evolution, at greater emitted photon energy. There is optimism that Swift will identify X-ray afterglows emitted earlier than the light from the first observed quasars.

5. Future Missions

Although we look forward to many years of active service from Chandra and XMM-Newton as well as the upcoming launches of INTEGRAL (2002), Swift (2003), ASTRO E-2 (2005) and GLAST (2006), there are also longer range plans to construct more powerful telescopes like Constellation-X, EXIST, LOBSTER, Generation-X and XEUS. The problems discussed at this meeting are already rewriting the scientific case for the longer term missions and it is hoped that this will be reflected in further improvements in mission design and optimal use of over-subscribed international resources for space astronomy.

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