THE ENERGETIC UNIVERSE

X. Barcons[1]

Instituto de Física de Cantabria (CSIC-UC), E-39005 Santander, Spain

Abstract

In this paper I review the main topics on the energetic Universe that have been put forward as main science goals in the Cosmic Vision 2015-2025 exercise. I discuss the study of matter under extreme conditions (both under strong gravity and at ultra-high densities), the cosmology of baryons (assembly of ordinary matter in dark-matter dominated structures and the creation of heavy elements) and the co-eval growth of super-massive black holes and stars in galaxies along cosmic history. Most of these topics can be addressed with a large-aperture deep Universe X-ray space observatory that can be flown soon after 2015, complemented by gravitational wave observatories (LISA), a focussing gamma-ray observatory, a far infrared high-sensitivity observatory and an X-ray survey telescope.

Key words: Black holes, Neutron Stars, Large-scale structure of the Universe, Galaxies: Active, Formation

1. Introduction

Energetic phenomena occur throughout the Universe. From the Earth's magnetosphere all the way through the most distant quasars, not forgetting about the very early Universe, there are places and times in the Cosmos where particles acquire high energies. These are often released as high-energy electromagnetic radiation (X-rays and γ-rays), which allows us to detect and study them out to very large distances. Very often, energetic phenomena are powered by strong gravity fields (around compact stars and black holes - BH), or very extended potential wells (groups and clusters of galaxies), strong magnetic fields (neutron stars) or the combination of various of these phenomena (e.g., active coronal stars).

Astronomical observations in the high-energy domain are currently enjoying a very particular era. The most powerful X-ray observatories in orbit launched in 1999, NASA's *Chandra* (Weisskopf et al. 2000) and ESA's *XMM-Newton* (Jansen et al. 2001), have been very recently joined in orbit by JAXA's *Suzaku* (formerly ASTRO-E2). At γ-ray energies, ESA's *INTEGRAL* is performing smoothly since October 2002 (Winkler et al. 2003). These and other space X-ray observatories are complemented by a number of ground-based facilities sensitive to very high γ-ray energies.

The Cosmic Vision 2015-2025 exercise has provided an opportunity to revise the most challenging and exciting science that can be performed in the realm of the energetic Universe in the decade after next, when the current facilities in orbit have been fully exploited. This presentation is an attempt to review some of what have been considered the most outstanding scientific goals in that domain for the 2015-2025 timeframe. These have been grouped under 3 main headings: matter under extreme conditions (Section 2, the assembly of baryons in Cosmological structures (Section 3), and the evolving violent Universe (Section 4). Finally I outline in Section 5 the main space tools that will be needed to address these extremely interesting topics in the 2015-2025 timeframe.

2. Matter under extreme conditions

Testing the intimate nature of matter and of the interactions among its constituents requires very challenging conditions. Ground-based particle accelerators, such as LHC at CERN or Tevatron at Fermilab, are designed and built to probe the behaviour of matter at very high energies and to probe the fundamental interactions among particles. The elementary constituents of matter, now believed to be quarks and leptons, have been studied to unprecedent detail with such experimental devices. So have been the short-ranged weak and strong fundamental interactions among these particles, as well as the electro-weak interaction which unifies one of them with the long-range electromagnetic interaction. In the foreseeable future, trails of a further unification, that of the electro-weak force with the strong nuclear one (the one that keeps the quarks bound inside nucleons), are expected to be seen by colliding matter and antimatter at the highest energies.

The Universe itself, however, provides us with places where the environmental conditions can be as extreme, or more, than in any existing or foreseen laboratory. The fourth of the fundamental forces of nature, gravity, has a tiny direct effect on the interactions between elementary particles in a laboratory experiment, but can be dominant under cosmic conditions. Indeed, the strongest gravitational fields in nature are those around neutron stars and black holes (BH). How does matter behave under the influence of gravity in the realm of General Relativity, well

Proc. 39th ESLAB Symposium, Noordwijk, 19–21 April 2005, F. Favata, A. Gimenez. eds.

beyond the post-Newtonian or any similar perturbative deviation from Newtonian gravity, can only be studied by observing the immediate vicinity of black holes and compact stars. Moreover, nuclear matter inside neutron stars is in such a high density (and low temperature), thanks again to gravity, that these conditions cannot be reached in any laboratory. Although that matter cannot be directly observed, the physics of strong interactions dictates its equation of state and therefore the mass and radius of the neutron star, which are potentially measurable quantities. Astronomical observations, mostly in the high-energy domain, can and will provide an important insight into the behaviour of matter under such extreme conditions.

2.1. Matter under strong gravity

General Relativity (GR) is indeed the best ever formulated theory of gravitation. GR predicts deviations from Newtonian gravity that have been confirmed and measured very accurately in the weak field limit. Figure 1 shows the portions of parameter space spanned by the most representative experiments and tests of GR. Most of these are concentrated in the weak gravitational potential limit ($\phi/c^2 = GM/(Rc^2) << 1$) and, since most of them are related to the gravitational field of the Sun or other stars (the binary pulsar) or the Earth, they are strongly clustered in the low mass corner. So far, no deviations from the predictions of GR have been reported by any experiment, and there is no reason to believe that GR will not describe gravity correctly in all the corners of this parameter space.

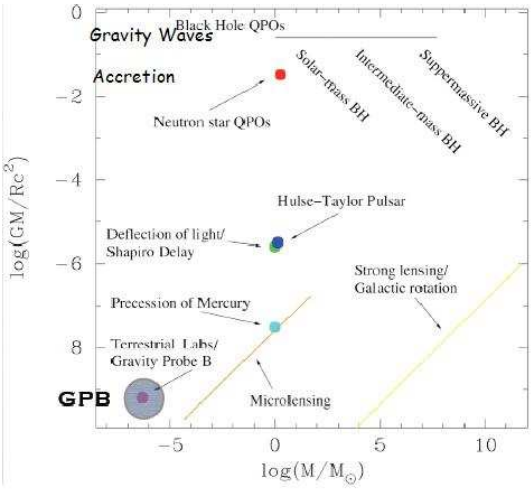

Figure 1. Tests of General Relativity at various field strengths and mass scales. The strong field limit (top part of the diagram) can be reached either by observing Gravity Waves or high-energy radiation from accreting material

In the strong field limit, GR predicts a suite of phenomena which are no longer small perturbations of Newtonian gravity, and which reflect a strongly curved space-time: strong gravitational redshift, Lense-Thirring precession, etc. These phenomena need the gravity of a black hole or a neutron star to be revealed. Strong variations in these strong gravitational fields will produce gravity waves that will be the ultimate probes of the behaviour of space-time closest to the event horizon. Accretion of matter around a black hole or a neutron star can also probe the curved space-time within a few Schwarzschild radii. High-energy (X-ray and γ-ray) radiation from the innermost regions of the accreting material can be used to reveal GR effects in the strong field limit, and to test this theory where its most spectacular effects are expected. Besides that, black holes span a very wide range in masses, from a few $M_\odot$ in “stellar” black holes to super-massive black holes ($> 10^{5-9} M_\odot$) in the centers of active galaxies (AGN), along with the newly reported intermediate mass black holes ($10^{2-4}\, M_\odot$).

One of the effects of strong gravity on the high-energy emission from accretion disks is the broadening of X-ray emission lines. The Fe Kα line (at 6.4 keV for neutral Fe), which has been and will continue to be the best handle for this, likely arises from fluorescence as the accretion disk is irradiated by the primary X-ray source. In the innermost parts of the accretion disk, where most of the power is produced, this line is broadened by various effects (Fabian et al. 1989), which include the Doppler effect, relativistic beaming, and gravitational redshift due to the nearby presence of the black hole. The resulting line profile is skewed towards softer photon energies due to this last effect. In AGN the much more distant obscuring “torus can also reflect primary X-ray radiation, but without any of these broadening effects.

The specific profile of the Fe line depends on many parameters (disk inclination, among others), but the importance of the low energy tail is dictated by how close the reflecting material orbits around the black hole. This, in turn, depends on the spin of the black hole, because the Innermost Stable Circular Orbit (ISCO) decreases as the spin parameter of the Black Hole $a = J/Mc$ increases (Bardeen et al. 1972). For a non-rotating (Schwarzschild) black hole, $R_{ISCO} = 3R_S$, where the Schwarzschild radius is $R_S = 2GM/c^2 = 3(M/M_\odot)$km, but for a maximally rotating Kerr black hole ($a \sim GM/c^2$) the Fe atoms can orbit much closer to the black hole $R_{ISCO} \sim 0.5R_S$. To illustrate this in simple terms, the closer to the BH that the Fe line is emitted, the deeper in the gravitational potential well that X-ray photons will have to escape from and the higher the fraction of their energy they will have to employ to reach the observer. Fig. 2 shows the Fe line profile for a non-rotating Schwarzschild and a maximally rotating Kerr black hole, assuming that the X-ray emissivity profile is highly concentrated in the innermost region of the accretion disk (emissivity $\propto r^{-3}$).

Tanaka et al. (1995) reported the first clear detection of a relativistically skewed Fe line profile from the bright

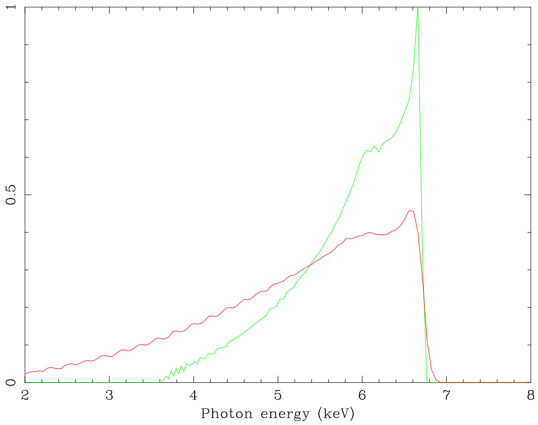

Figure 2. Relativistic Fe line emission profile for non-rotating (green, more peaked) and maximally rotating black holes (red, less peaked.

Seyfert 1 galaxy MCG-6-30-15 observed with ASCA. Studies of the time variations of this line (Iwasawa et al. 1996) with the same data, already indicated that the BH could be rotating. Higher sensitivity observations conducted with ESA's *XMM-Newton* (Wilms et al. 2001, Vaughan & Fabian 2004) confirm the relativistic profile of the line and clearly call for a rapidly spinning BH (see Young et al. 2005 for a compilation of *XMM-Newton* and *Chandra* X-ray spectroscopy on this object). Fig 3 shows the average X-ray spectral profile of the Fe Kα line for MCG-6-30-15, where it is shown that the red wing extends down to ~ 3 keV, implying $a/M > 0.7$.

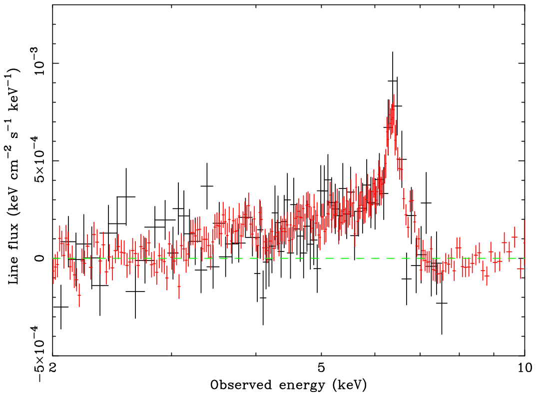

Figure 3. Observed Fe line profile for the Seyfert 1 galaxy MCG-6-30-15 from Young et al (2005).

There are indeed a number of AGN where a relativistically broadened Fe line has been seen (e.g., NGC 3516 Turner et al. 2002) , but in many of the best studied cases the broad red wing is either absent or difficult to see. A narrow Fe line, arising from reflection in the far more distant molecular torus where no kinematical or relativistic effects are expected, appears to be ubiquitous (Yaqoob & Padmanabhan 2004). A combination of both narrow and broad components is illustrated in the case of Mrk 205 (Reeves et al. 2001). Note also that in the case of MCG-6-30-15 (fig. 3) the red wing of the Fe line does not exceed 5-10% of the underlying continuum in most of the spectrum, and therefore its detection requires extremely high sensitivity, something only achievable for the brightest AGN.

The chances of extending the studies of matter under strong gravity fields to more distant supermassive BH have been revived by recent work by Streblyanska et al. (2005) and Brusa et al. (2005). These studies show that the average X-ray spectrum of distant AGN and QSOs does show a strong Fe line signal (in fact, implying a factor 3 overabundance of Fe with respect to solar values), with broad profile which is reminiscent of a rotating black hole.

Relativistic Fe line profiles have also been seen in Galactic black hole candidates. Cygnus X-1 (see Reynolds & Nowak 2003 for a review on the difficulties in detecting this feature) and XTE J1650-500 (Miller et al. 2004) are among the best studied cases. In the latter, for instance, there is evidence that reflection occurs at radii well below the ISCO for a non-rotating BH, implying rapid spin.

High-energy radiation from accreting material onto BHs is highly variable. Since the Fe line emission is expected to arise from reflection, it should follow the variations on the incident continuum that can also be monitored in line-free regions of the high-energy spectrum. If X-ray spectral variations could be tracked down to individual orbit scales, then the whole geometry of the space-time around the BH could be tested.

Nature is, however, not so simple as revealed in the first attempt to perform "reverberation mapping on the *XMM-Newton* X-ray data from MCG-6-30-15 (Vaughan & Fabian 2004). The analysis reveals that the X-ray spectrum is composed of a roughly constant and strong reflection component which does not respond to a weaker but highly variable underlying continuum. Miniutti & Fabian (2004) propose a model to explain this that invokes another prediction of GR which is strong light bending. The fundamentals of that model reside in the fact that when most of the emission occurs at low latitudes, the amount of reflection is much larger because the strong BH gravity bends most of the light from the far side of the BH towards us. In such situation we do see a strong reflected component which should be mostly insensitive to small continuum variations. When the emission occurs at significantly higher latitudes, light bending is less important, the reflection component is weaker, the source is weaker and we should then expect a nicer correlation between incident (direct) radiation and the strength of the Fe line. Indeed, specific computations of this effect should take account of all GR effects at their full strength.

As it has already been pointed out, the ultimate goal of these X-ray spectral variability studies should be to go down to individual orbits. A remarkable case, where this might have been already achieved, is that of NGC 3516

(Iwasawa et al. 2004). The time -averaged X-ray spectrum of this source exhibits a strong Fe line at 6.4 keV and a weaker redshifted line at 6.1 keV. A time-resolved study shows that while the strong blue line is constant, the red one goes on and off with an apparent periodicity of 25 ks during a few cycles. This is what is expected if there is some feature in the reflecting material rotating very close to the BH. Note that this can yield an indication of the mass of the BH (in this case $\sim 10^7\,M_\odot$). The possibility of measuring the mass of BHs, by studying spectral variations in individual orbits is one of the "holy grails in this field.

But orbital motions around BH and NS can also be studied by accumulating the X-ray light emitted in a broader bandpass, without going into the details of the X-ray spectral features. Timing studies of accreting material around BHs and NS reveal the frequencies of its motion via the power spectrum (Fourier transform) of the X-ray flux time series. The power spectra display a superposition of noises (very broad features or continua) and broad peaks called Quasi-Periodic Oscillations (QPOs). The latter are expected to correspond to the proper frequencies of the motion of the accreting material around the compact object. For a stellar BH with mass $10\,M_\odot$, and assuming that emission occurs at the ISCO, the Keplerian frequency ($\nu_K = \sqrt{(GM/r^3)}/(2\pi)$) occurs at ~ 200 Hz and for a NS with mass just above the Chandrasekhar limit ($1.4\,M_\odot$) the orbital frequency exceeds 1 kHz. Therefore, msec timing is the key ingredient to characterize motions around $< 10\,M_\odot$ compact objects.

The solution of the equations of motion in a Kerr spacetime predicts 3 fundamental frequencies, as the GR motion does not occur in a plane, nor does it describe closed orbits. These frequencies are called *orbital* ν_ϕ (which in the absence of rotation of the central object reduces to the Keplerian frequency), *radial* ν_r and vertical ν_θ epicyclic. All 3 frequencies are equal to the Keplerian orbital frequency in Newtonian mechanics, but in GR ν_r is different -independent on the spin parameter of the Kerr metric- , and ν_θ also differs from the orbital frequency if the compact object rotates. This leads to several predictions. First, regardless on whether the compact object rotates or not, there is a periastron precession with frequency $\nu_{peri} = \nu_\phi - \nu_r$, as in the well studied classical GR test of Mercury. If the compact object rotates, then $\nu_\phi \neq \nu_\theta$ and there is Lense-Thirring precession of the orbital plane (i.e., the plane of the orbit precesses around the spin of the compact object) with nodal frequency $\nu_{nodal} = \nu_\phi - \nu_\theta$.

The very detection of the ISCO around a BH or a NS is in itself a confirmation of General Relativity. If the mass of the compact object were known, its spin could then be deduced. kHz QPOs have been indeed detected in a number of Galactic Black Hole candidates and Neutron Stars (particularly with NASA's *RXTE* observatory, Bradt et al. 1993), but the interpretation of the various peaks in the Fourier spectrum is not straightforward and appears complicated. Relations involving the width of the various frequency peaks ($\Delta\nu$), their coherence ($\nu_0/\Delta\nu$), etc. need to be used in the framework of different models to understand the full QPO spectrum (van der Klis 2004). Every model (relativistic precession, relativistic resonance, frequency beating etc.) predicts a number of distinctive imprints in the power spectrum, particularly at low frequencies. There is general belief that this technique can provide a detailed insight on the motions of the accreting material in the strongly curved space-time around a BH or a NS. The best approach would be, however, to have the possibility to study orbits individually, i.e., to have a very high-throughput X-ray detector capable of reliably measuring high-accuracy fluxes every fraction of a msec orbit.

2.2. Matter at supra-nuclear densities

Neutron stars are amongst the densest objects in the Universe, with their core density being 5 to 10 times larger than an atomic nucleus. The physics of matter at these densities is largely unknown. From the phenomenological point of view, laboratory ion-collision experiments can only partially approach the environmental conditions in the core of a NS, because the different "temperature and also the different proton fraction (typically very small in NS). Uncertainties in the symmetry energy function in the energy of a nucleonic system are already large at nuclear densities (it combines a term scaling with nuclear mass and another one with the surface which are difficult to disentangle), and extrapolations at significantly higher densities make the situation even worst. For a review see Lattimer & Prakash (2004).

From the theoretical point of view, the situation is not any better. The "classical composition of a NS with a majority of neutrons and a tiny fraction of protons (with the corresponding neutralizing electrons and muons) has many chances of being too simplistic at supranuclear densities. The core of a NS could be well rich in pion or kaon condensates or it could consist of a soup of unconfined quarks (see Lattimer & Prakash 2001 for a collection of models). Even more, it could consist of "Strange" quark matter, i.e., a combination of the quarks u (up), d (down) and s (strange) with a considerably different set of properties. Each one of these possible compositions leads to a different equation of state (EoS). While it is not possible to probe directly the EoS at these densities, the mass and radius of the resulting NS is strongly affected by it. Figure 4 shows a selection of Mass-Radius relations for a number of equations of state, where it is seen that "Strange" stars predict significantly smaller masses than "normal" (with u and d quarks only) stars.

NS masses can be best measured in close compact binaries, such as the binary pulsar PSR 1913+16, where Shapiro delay or orbital period variations due to the loss of energy by Gravitational radiation, can disentangle indi-

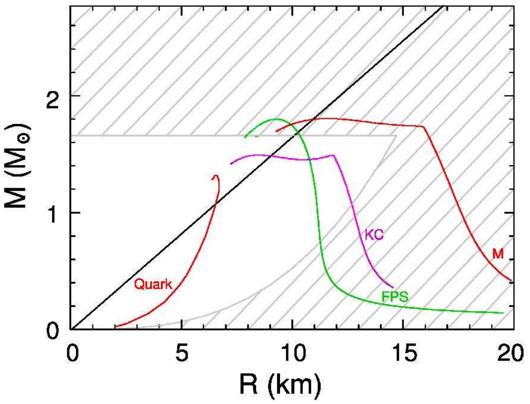

Figure 4. Mass-Radius parameter space for Neutron Stars, along with predictions from various EoS. The dashed region is excluded by assuming the detection of orbital motion at $\nu_{orb} = 1\,\mathrm{kHz}$*. The diagonal line corresponds to a surface redshift of* $z_{grav} = 0.35$*.*

vidual masses. In this case, the mass is $1.44\,M_\odot$. Causality (the speed of sound has to be less than the speed of light) sets up an upper limit to the NS mass at around $3\,M_\odot$.

As far as measuring NS radii are concerned, the situation is more difficult, with the possible exception of NS of known distance and under the assumption of a Stefan-Boltzmann (black body) emission law. There are, however, X-ray observations that can help measuring M and R for neutron stars. Following with the timing analysis discussed under 2.1, the detection of the frequency of orbital motion ν_{orb} from kHz QPOs places useful constraints on the M-R parameter space. This comes simply from the fact that $R_{orb} > R_{ISCO}$ and that $R < R_{ISCO}$. In fig. 4 we display the region excluded, assuming that orbital motion has been detected at 1 kHz.

An alternative method to constrain this diagram, even for isolated neutron stars, has been put forward by Cottam et al. (2002). The NS EXO 0748-676 occasionally bursts material, and the photospheric absorption lines in its X-ray spectrum are affected by the strong gravity at the NS surface. By adding the X-ray spectra of 26 bursts, Cottam et al. (2002) were able to measure a gravitational redshift of $z = 0.35$ at the surface of this NS. This implies a roughly constant value for M/R which is also displayed in fig. 4.

More detailed information on the EoS of matter at supranuclear density could be gained if X-ray spectra could be obtained with very high signal to noise and at high spectral resolution, since the Stark effect due to the electric field at the NS surface would broaden the photospheric absorption lines with FWHM $\propto M/R^2$. Detection of this pressure broadening would break the degenracy between M and R set by the gravitational redshift and measure M and R to sufficient accuracy to single out an EoS.

3. The Cosmology of baryons

After years of experiments and observations, a consensus has been reached among cosmologists about the basic ingredients of the Universe. The Universe began some 14 billion years ago in a big event (the Big Bang) where the ordinary laws of physics do not apply. The first direct electromagnetic radiation that we receive from the past of the Universe is the Cosmic Microwave Background (CMB), which results from the recombination of electrons and protons to form atoms, when the universe was less than half a million years old. CMB maps reveal an extremely uniform Universe at that epoch, but with small wiggles which were the seeds of the large-scale structures that we see today. How the Universe went from an extremely smooth phase to the highly structured situation we see today, with clusters, superclusters, voids, filaments and all sorts of structures, is the main goal of Astrophysical Cosmology.

Today, ordinary, baryonic matter represents 4-5% of the total content of the Universe, and almost half of it is in an unknown location. About 23% is made of Dark Matter (DM), which binds galaxies and clusters via gravitational attraction (the only manifestation of DM so far). The bulk of the Universe is contributed by an even more exotic, extremely uniform component, Dark Energy (DE), which in fact shapes the geometry of the Universe and acts as a peculiar “repulsive force. The relative amount of DM and DE changes with cosmic time, and it is expected that in the past the Universe was DM-dominated rather than DE-dominated as it is today. DM is approximately pressureless, but DE has, to first order, the pressure of an unstable vacuum $p_{DE} = -\rho_{DE}c^2$, which gives it this particular “accelerating character in the history of the expansion of the Universe.

In principle, only the 4-5% of the baryons is all we can observe via electromagnetic radiation. The DM potential wells of groups and clusters of galaxies, the largest gravitationally bound structures in the Universe, have virial temperatures which imply X-ray temperatures for the baryons trapped in them. Indeed, groups and clusters are X-ray emitters. Tracing the history of the assembly of baryons into these large-scale structures, finding the almost 50% of them which are missing (probably in a warm/hot intergalactic medium), and studying when and where the heavy elements of which the current Universe is made of were produced along cosmic history are amongst the most important goals in what can be called the ”Cosmology of ordinary matter”. X-ray and γ-ray radiation are the best handles towards that goal.

3.1. Birth & growth of galaxy clusters

The gravitational attraction produced by DM is the prime actor in the assembly of groups and clusters. Gravity binds the baryons together and heats the intra-group or intracluster gas to high temperatures. However, this is not the end of the story, as gravitational heating would predict, for example, a relation between the X-ray gas luminosity and temperature $L_X \propto T^2$, while a significantly steeper scaling law ($L_X \propto T^3$) is observed (Arnaud & Evrard 1999). The “entropy floor discovered in groups of galaxies (e.g., Ponman et al. 2003), and unlikely to be produced by an overall pre-heating process, is another manifestation of the complexity of the problem.

Gas cooling at the cluster centers, heating by Supernovae or AGN are ingredients that surely come into play in determining the structure of groups and clusters. Thanks to *XMM-Newton*, it is now known that cooling of the baryons in cluster cores is not so dramatic as predicted by the older cooling flow models (e.g., Peterson et al. 2003), with little gas cooling below 2 keV. Fabian et al. (2003) argue in the case of the Perseus cluster that the continuous blowing bubbles of electron gas by the central radio AGN, can balance the cooling within the cluster core.

To understand how groups and clusters form, it is first necessary to disentangle the role of the various processes that affect the cluster entropy (cooling, Supernova and/or AGN heating) for a range of cluster masses and at various epochs of cosmic history. Obtaining temperature and gas density cluster profiles spanning a wide range of cluster mass and redshift is the way to go. The detailed physics of baryons in cluster cores will in addition require high-spectral resolution, spatially resolved X-ray spectroscopy of cluster cores. Last, but not least, the role of turbulence, high energy tails (discovered in several clusters of galaxies), cosmic rays (of which clusters are full), magnetic fields and other energetic phenomena will also require γ-ray observations of clusters. Most of these are beyond the capabilities of present X-ray and γ-ray instrumentation.

Once it is known how clusters work, there is the possibility of using them as cosmological tools, being the most massive gravitationally bound structures. The population of clusters is indeed very sensitive to the values of cosmological parameters (Griffiths et al. 2004). The DUO (Dark Universe Observatory) mission proposal, showed that by studying the number of clusters as a function of redshift, one can derive not only the amount of DM and DE, but also the equation of state of DE. A further crucial piece of information can be obtained from the spatial distribution of clusters, by sampling sufficiently large contiguous areas of the sky.

Further information on the Cosmological parameters can be gained by studying the cluster gas fraction for large and relaxed clusters as a function of cosmic history, as recently discussed by Allen et al. (2004). The gas fraction (baryon to DM mass) in these objects is supposed to be representative of the full Universe on average and therefore should be constant along cosmic history. Estimating both the gas mass and the DM mass from observable quantities involves the use of the luminosity distance which in turn depends on the Cosmological parameters. Current studies are very short on the amount of high-redshift clusters, but already indicate that the concordance cosmological parameters discussed above give a much better fit than other cosmological parameters, for example a standard Cold Dark Matter one (see fig. 5, from Allen et al. 2004).

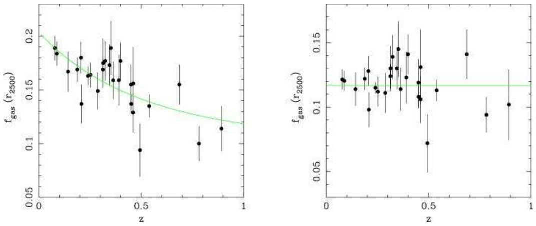

Figure 5. Gas fraction of clusters as a function of redshift for a CDM cosmology (left) and a concordance cosmology (right), adapted from Allen et al (2004).

3.2. The missing baryons

The baryonic component of the Universe is well restricted by several Cosmological tests (including primordial nucleosynthesis, Kirkman et al. 2003 and CMB anisotropies, Bennet et al. 2003) to be around 4.5%. Lyman-α clouds (including damped Lyman-α absorption systems) detected as HI Lyman-α absorption lines towards distant QSOs are seen to dominate the baryon content of the Universe at high redshift ($z > 2$, Storrie-Lombardi & Wolfe 2000). At lower redshifts the number density of Lyα absorbers and the subsequent contribution to the ordinary matter content of the Universe decrease. Nicastro et al. (2005) estimate that the total budget of baryons is locally 2.5% of the total content of the Universe, with a further 2.1% (i.e., about half of the total amount of baryons) missing.

Detailed simulations of the cosmological evolution of baryons invariably show that the Lyman-α absorbing gas at temperatures $\sim 10^4$ K undergoes shock heating at lower redshifts and its temperature rises to 10^{5-7} K. According to these simulations, baryons in this warm and hot intergalactic medium (WHIM) could probably account for the missing fraction of the baryon budget in the local Universe. These baryons are expected to be distributed following filamentary structures dictated by the underlying DM distribution.

Given the sparsity of these baryons in the WHIM, they would be best seen via resonance absorption lines of highly ionised species (OVI, OVII, OVIII, NeIX, etc.) towards bright background sources (typically AGN). Most of these lines occur in the soft X-ray regime, and therefore sensitive high-resolution X-ray spectroscopy is the best tool for this purpose. *Chandra* and *XMM-Newton* have already started the run to detect absorption lines from the WHIM, with a handful of positive hits - many of them arising in local gas (Nicastro et al. 2002, Rasmussen et al. 2003). Nicastro et al. (2005) compute that, within (large) errors, the mass contained in the WHIM is consistent with the missing fraction of baryons.

The observations needed to detect these absorption lines are at the very limit of contemporary X-ray instrumentation. Both larger effective area and better spectral resolution are needed to sample a large number of lines of sight to improve the statistics and to trace the filamentary structures predicted by the simulations, as well as to reach significant redshifts to test how baryons in the intergalactic medium are heated towards the current epoch.

3.3. The creation of heavy elements

The heavy elements that constitute the Universe today, were produced in stellar cores and dispersed in Supernova explosions. Locally, the detection of elemental abundances in Supernova Remnants (SNRs) is the most direct way to study this process. Spatially resolved X-ray spectra of SNRs show in detail how the various elements are propagated into the interstellar medium. Nuclear lines observed in γ-rays can also determine elemental abundances, in particular of heavy rare elements.

Beyond our Galaxy and perhaps a few more in the Local Group, intracluster gas is probably the best tracer of heavy element abundances as a function of redshift. X-ray spectra of clusters are rich in emission lines superimposed to thermal bremsstrahlung. From the line emission, elemental abundances of a variety of elements can be derived, and related to the history of star formation. The Fe abundance is easier to obtain, as the Kα complex at 6-7 keV is usually strong and isolated from other spectral features. Obtaining abundances of other elements (Mg, O, Si, etc.) needs observing at softer X-ray energies, which would usually require higher resolution spectroscopy.

One of the most intriguing results found in this area is that the Fe abundance in clusters stays approximately constant at 0.3 of the solar value, out to the highest redshifts ($z \sim 1.1$, Hashimoto et al. 2004). This means that heavy elements are already in place at these early epochs, and therefore most of the enrichment in heavy elements has happened before. However, the number of clusters at $z > 1$ is very small, and the detection of line emission from them is at the limit of the capabilities of current instrumentation. To trace the history of heavy element enrichment more sensitive X-ray observatories equipped with high-resolution spectrometers are needed.

4. The evolving violent Universe

One of the very first discoveries of X-ray Astronomy was the Cosmic X-ray Background (XRB, Giacconi et al. 1962). This energetic radiation that fills the Universe is known today to be the integrated radiation produced by accretion onto supermassive black holes (SMBH) along cosmic history. These grown SMBHs are those that we see today in the centers of virtually all galaxies and that comprise $\sim$ 0.4% of their bulge mass (Ferrarese & Ford 2005). According to the AGN unified models for the XRB (Comastri et al. 1995), most of this accretion occurs in obscured mode (more than 50% of it, Fabian & Iwasawa 1999), and therefore its direct detection can only be achieved in hard X-rays.

This general qualitative picture of the XRB being the echo of the growth of the supermassive black holes opens a number of questions. The first one is how SMBHs (or their seeds) were born and whether they can be detected or not at the time of birth. The second one is how they grow from their probably small initial mass to their very large masses that we see today ($> 10^9\,M_\odot$). Finally there is the question on how the birth and growth of SMBHs relates to the formation of galaxies and their stars. We have now clear clues that there is a link between both processes, but how exactly they work is not yet understood.

There are a number of additional questions regarding the evolving violent Universe, some of which might certainly be related to the topics just discussed. One of the outmost importance is the nature of Gamma Ray Bursts, and whether any of them (perhaps yet to be discovered) are related to the birth of SMBHs. This and other topics will certainly meet progress within the Cosmic Vision 2015-2025 timeframe.

4.1. Birth & growth of supermassive black holes

Numerical simulations show that the very first stars that formed in the Universe grew up from a seed of about $\sim 1 M_\odot$ to a few hundred solar masses within a few million years (Abel et al. 2002). These stars exploded leaving a BH of mass of a few $\sim 10\,M_\odot$, and sterilizing a large region ($\sim 10^6\,M_\odot$) for further star formation around them. According to the numerical simulations, these seed BHs left the scene at a relatively large velocity ($\sim 10\,\mathrm{km\,s^{-1}}$) and it is therefore unclear whether all of them were able to start any efficient accretion process.

These first small BHs that formed early on in the history of star formation, could well be the seeds of their grown-up version that we see in the centers of galaxies today. For this to happen, they need to accrete matter rapidly, in an almost exponential fashion (Archibald et al. 2002). Massive BHs ($\sim 10^8\,M_\odot$) are already in place in the most luminous QSOs found at early epochs ($z > 4$). This means that by $z \sim 10$ the first mini-QSOs, hosting a BH of mass $\sim 10^4\,M_\odot$, should be there accreting close to the Eddington limit.

Copious X-ray radiation, and in particular in hard X-rays for obscured objects, is emitted during the growth phase by accretion of the SMBHs. X-ray deep surveys (see review by Brandt & Hasinger 2004) are then the best tool to characterize the first stages of the growth of black holes by accretion. Indeed, other processes might also be important in the growth of black holes, namely merging or tidal capture. To first approximation and to the best of today's knowledge, highly efficient (probably requiring rotating Kerr BH) accretion is probably the dominant process (Marconi et al. 2004) in the “growth of SMBH, as it can match the AGN X-ray luminosity functions (the output from accretion) to the local SMBH density (see fig. 6). The birth of SMBHs is not well understood. The galaxy merger rate peaks at $z \sim 2$, which is where the unabsorbed type 1 AGN population also peaks, implying that mergers might be important. However, the role of type 2 AGN, whose population peaks at significantly later epochs, is not known. Whether these are two distinct unrelated populations, or follow some sort of evolutionary sequence is an open and debated question.

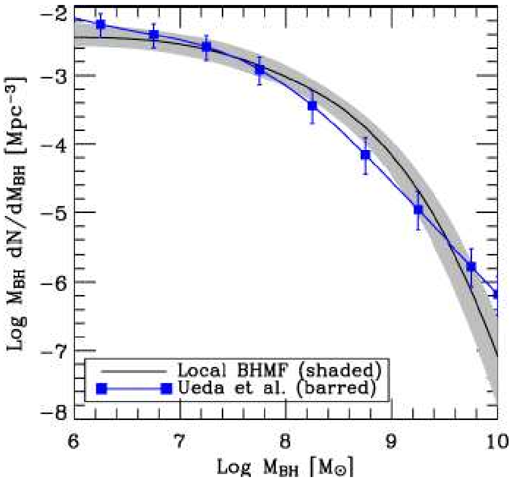

Figure 6. Local SMBH function as observed from galaxy kinematics (dots) and as computed by assuming efficient accretion growth in AGN (adapted from Marconi et al 2004).

The XRB remains a key handle to quantify the amount and “mode of accretion. Most of its energy density resides at $\sim 30\,\mathrm{keV}$ (see, e.g., Fabian & Barcons 1992 for a review), implying that an important fraction of the energy generated by accretion onto SMBHs is heavily obscured. Current instruments (*XMM-Newton*, *Chandra* and *Integral*) are not sensitive enough at these energies, and therefore not much can be said beyond extrapolations. Sensitive instruments at these hard X-ray/soft γ-ray energies are needed.

4.2. SUPERMASSIVE BLACK HOLES AND STAR FORMATION

The birth and growth of SMBHs in the centers of galaxies cannot be independent of the birth and growth of the galaxies themselves and the stars in them. How this proceeds and what are the physical links between both SMBH and star formation remains to be understood.

Phenomenological links between SMBH growth and star formation have been found over the last years by comparing X-ray fluxes to submillimeter observations. The first clue of co-eval SMBH growth and star formation in AGN was reported by Page et al. (2001), where it was found that half of the X-ray emitting AGN were also strong submillimeter emitters, implying high star formation rates. It is also known that at least $\sim 40\%$ of star-forming submillimeter emitting galaxies contain a growing SMBH emitting X-rays. Page et al. (2004) (and see Fig. 7) find that star formation, as revealed by submillimeter emission, is much stronger in obscured accreting SMBHs than in unobscured QSO-type X-ray emitting AGN. This suggests that SMBHs undergo a growth phase co-eval with copious star formation, then they shine as type 1 unobscured AGN and when there is no more material to accrete SMBHs stay dormant in galactic centers as we see most of them today.

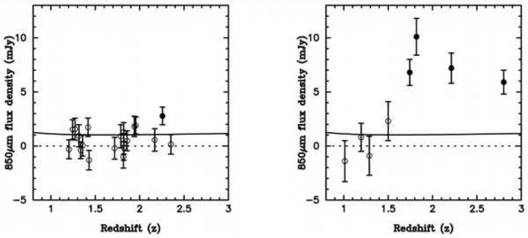

Figure 7. Submillimeter emission for a sample of unobscured AGN (left) and obscured AGN (right), showing that star formation is far more important in the latter (adapted from Page et al. 2004)).

Di Matteo et al. (2005) have recently conducted simulations that simultaneously follow star formation and the growth of black holes during galaxy-galaxy collisions. In the collision there is a burst of star formation, and large amounts of gas are funneled to the SMBHs leading to copious accretion. The energy released ends up expelling gas and preventing further star formation and SMBH growth after a short phase of 100 million years (see Fig. 8). Di Matteo et al. (2005) also compute the star formation rate in the absence of SMBH, leading to a much weaker peak during the merging epoch but with a sustained rate after the merging. It is then clear that SMBH accretion gives first a burst of star formation, but after the collision it suppresses star formation.

To properly test these models and to witness how SMBH growth and star formation in galaxies are related along cosmic history, deep X-ray surveys need to be combined with deep surveys in the far-infrared. Space observatories operating at these wavelengths need to be priorities in Cosmic Vision 2015-2025.

5. WHAT TOOLS ARE NEEDED?

Previous sections present a number of very exciting questions about the energetic Universe that are being put for-

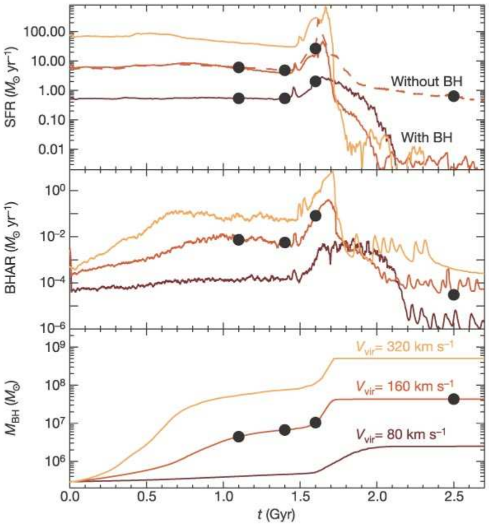

Figure 8. Star formation rate (top), SMBH accretion rate (middle) and SMBH mass (bottom) as a function of time in a galaxy-galaxy collision. The top panel also illustrates what is the effect of the SMBH accretion (adapted from Di Matteo et al 2005).

ward by scientists working in the field. These questions can be summarized as:

- How does matter behave under very strong gravitational fields or at supra-nuclear densities?
- How do baryons assemble into cosmic structures? Where are all missing baryons gone? When, how and where were the heavy elements present in today's Universe produced?
- How do supermassive black holes grow, what are their parent seeds and how are black hole growth and star formation related?

The main space tool urgently needed in the 2015-2025 decade to address most of these questions is a large aperture (effective area $\sim 10\,\mathrm{m}^2$ at 1 keV), high angular resolution (< 5") X-ray observatory. This telescope should be equipped with a payload complement on its focal plane that allows scientists to conduct large field-of-view deep imaging, high spectral resolution spectroscopy at X-ray energies from 0.2 to 8 keV, a detector that can handle large count rates from bright sources to perform timing analysis, and a facility that extends the performance of this telescope system beyond 30 keV. In the paper by E. Costa et al. (these proceedings) the advantages of adding a polarimeter are highlighted. With such an observatory in operation, the vast majority of the scientific questions raised in this paper sould find an answer.

ESA and JAXA have been studying a mission called XEUS (X-ray Evolving Universe Spectroscopy mission[1]) for a number of years, in an attempt to fulfill the above requirements. NASA has also been studying a mission called *Constellation-X*[2] with a special emphasis on spectroscopy, but that could also deliver some of the science discussed in the present paper. Clearly a way ahead should be found that secures that soon after 2015 there is a large X-ray observatory-class space facility in operation.

The next tool obviously needed is a gravitational wave observatory such as LISA. This will help to detect steep variations of strong gravity fields (those produced by BHs) out to much larger distances than any electromagnetic radiation detector can reach. As it has been said in subsection 2.1, the ultimate probe of the structure of spacetime at the event horizon itself can only be addressed by gravitational wave observatories. An imaging γ-ray observatory will also be of enormous help in looking at the regions next to the event horizon as well as to detect traces of the rarest heavy elements via nuclear lines.

Next in the list, a far infrared observatory with enough sensitivity (i.e., effective area and angular resolution) that can trace star formation rates in obscured objects out to the redshifts where the first galaxies, along their stars and black holes, formed. In combination with the large aperture X-ray observatory, this will help us to understand the link between supermassive black hole birth and growth and star formation.

Last, but not least, a dedicated mission to survey large parts of the Universe with enough sensitivity (similar to DUET, DUO, LOBSTER or ROSITA) would find the most extreme objects in the Universe, build complete samples of rare energetic objects (such as luminous clusters of galaxies at early epochs) and will ultimately permit the use of galaxy clusters as cosmological tools.

Too much, perhaps, for a single decade and meagre budget. However, the scientific challenge and excitement is there and will not disappear.

Acknowledgements

I'm grateful to many colleagues for help in the preparation of this presentation and for long-standing collaborations in the field: M. Arnaud, D. Barret, G. Bignami, J. Bleeker, F. Carrera, A. Comastri, A.C. Fabian, G. Hasinger, H. Inoue, H. Kunieda, J.-W. den Herder, M. Méndez, G. Palumbo, A. Parmar, M. Turner and C. Turon. Financial support was provided by the Spanish Ministerio de Educación y Ciencia, under project ESP2003-00812.

References

Abel T., Bryan G., Norman M.L., 2002, Science, 259, 93

Alcock C. & Olinto A., 1988, Annu. Rev. Nucl. Part. Sci., 38, 161

Alexander D.M. et al., 2003, ApJ, 125, 383

Alexander D.M., Smail I., Bauer F.E., Chapman S.C., Blain A.W., Brandt W.N., Ivison R.J., 2005, Nat, 434, 738

Allen S.W., Schmidt R.W., Ebeling H., Fabian A.C., van Speybroek L., 2004, MNRAS, 353, 457

Archibald E.N., Dunlop J.S., Jiménez R., Friaca A.C.S., McLure R.J., Hughes D.H., 2002, MNRAS, 336, 353

---

[1] http://www.rssd.esa.int/XEUS

[2] http://constellation.gsfc.nasa.gov

Arnaud M., Evrard A.E., 1999, MNRAS, 305, 613

Bardeen J., Press, W. & Teukolsky S., 1972, ApJ, 178, 347

Bennet C.L. et al., 2003, ApJS, 148, 1

Bradt H., Rothschild R.E., Swank J.H., 1993, A&AS, 97, 355

Brandt W.N. & Hasinger G., 2004, 43, 1

Brusa M., Gilli R., Comastri A., 2005, ApJ, in the press (astro-ph/0501542)

Comastri A., Setti G., Zamorani G., Hasinger G., 1995, A&A, 296, 1

Cottam J., Paerels F., Méndez M., 2002, Nat, 420, 51

Di Matteo T., Springel V, Hernquist L., 2005, Nat, 433, 604

Fabian A.C. & Barcons X., 1992, ARAA, 30, 429

Fabian A.C., Rees M.J., Stella L., White N.E., 1989, MNRAS, 238, 729

Fabian A.C. & Iwasawa K., 1999, MNRAS, 303, L34

Fabian A.C., Sanders J.R., Allen S.W., Crawford C.S., Iwasawa K., Johnstone R.M., Schmidt R.W., Taylor G.B., 2003, MNRAS, 344, L43

Ferrarese L., Ford H., 2005, Space Sci. Rev., 116, 523

Giacconi R., Gursky H., Paolini F.R., Rossi B., 1962, Phys. Rev. Lett., 9, 439

Griffiths R., et al., 2004, Proceedings of the SPIE, 5488, 209

Hashimoto Y., Barcons X., Böhringer H., Fabian A.C., Hasinger G., Mainieri V., Brunner H., 2004, A&A, 417, 819

Kirkman D., Tytler D., Suzuki M., O'Meara J.M., Lubin D., 2003, ApJS, 149, 1

van der Klis M., 2004, in Compact stellar X-ray sources, Lewin & van der Klis (eds), Cambridge University Press

Iwasawa K., et al., 1996, MNRAS

Iwasawa K., Miniutti G., Fabian A.C., 2004, MNRAS, 355, 1073

Jansen F.A., et al, 2001, A&A, 365, L1

Laor A., ApJ, 376, 90

Lattimer J.M. & Prakash M., 2001, ApJ, 550, 426

Lattimer J.M. & Prakash M., 2004, Science, 304, 536

Marconi A., Risaliti G., Gilli R., Hunt L.K., Maiolino R., Salvati M., 2004, MNRAS, 351, 169

Miller J., et al., 2004, ApJ, 601, 450

Miniutti G., Fabian A.C., 2004, MNRAS, 349, 1435

Nicastro F., et al., 2002, ApJ, 573, 157

Nicastro F., et al., 2005, Nat, 433, 495

Page M.J., Stevens J.A., Mittaz J.P.D., Carrera F.J., 2001, Science, 294, 2516

Page M.J., Stevens J.A., Ivison R.J., Carrera F.J., 2004, ApJ, 611, L85

Peterson J.R., Kahn S.M., Paerels F.B.S., Kaastra J.S., Tamura T., Bleeker J.A.M., Ferrgno C., Jernigan J.G., 2003, ApJ, 590, 207

Ponman T.J., Sanderson A.J.R., Finoguenov A., 2003, MNRAS, 343, 331

Rasmussen A., Kahn S.M., Paerels F., 2003, in Rosenberg J.L., Putman M.E. eds., *The IGM/Galaxy connection: the Distribution of Baryons at z=0.* ASSL Conf. Proc. Vol. 281. Kluwer, Dordrecht. p. 109.

Reeves J.N. et al., 2001, A&A, 365, L134

Reynolds C.S., Nowak, M.A., 2003, Phys. Rep., 377, 389

Storrie-Lombardi L., Wolfe A.M., 2000, ApJ, 543, 552

Streblyanska A., Hasinger G., Finoguenov, S., Barcons X., Mateos S., Fabian A.C., 2005, A&A, 432, 395

Tanaka Y., et al., 1995, Nat, 375, 659

Turner T.J., et al., 2002, ApJ, 574, L123

Vaughan S., Fabian A.C., 2004, MNRAS, 348, 1415

Weisskopf M.C., Tananbaum H., Van Speybroek L., O'Dell S., 2000, Proc. SPIE, 4012, 2

Wilms J., et al., 2001, MNRAS, 3218, L27

Winkler C., et al., 2003, A&A, 411, L1

Yaqoob T. & Padmanabhan U., 2004, ApJ, 604, 63

Young A.J., Lee J.C, Fabian A.C., Reynolds C.S., Gibson R.R., Canizares C.R., 2005, ApJ, in the press (astro-ph/0506082)