It is now widely recognised that massive black holes must have had a fundamental influence on the formation of galaxies and vice versa. With current and imminent missions we aim to unravel much of this relationship for the last 10 Gyr of cosmic history, while the quasar population waned and star formation died down. The picture at earlier times will be more difficult to reconstruct, but will likely be even more exciting: when the first stars shone, the first dust was formed, and quasars were a vigorously rising population. One of the primary goals of XEUS is to allow us to find and study the earliest quasars, however deeply buried in gas and dust they may be. But to understand fully the astrophysical context of these objects, their significance in the grand picture, we must learn how they relate to their environments and their host galaxies. The ESA future Far InfraRed Mission (FIRM) will provide much of the data we require, revealing the dust heated by star formation in the host galaxy, the relative evolutionary stages of spheroid and black hole, and the total energy budgets possessed by these first quasars. FIRM will reveal star formation in the immediate proto-cluster environment of the quasar and so tell us how the formation of the first galaxies and quasars coupled to the earliest large scale structures.

Key words: Stars: formation – Galaxies: formation – Galaxies: evolution – Quasars: general

1. Introduction

Three hundred and eighty thousand years after the big bang, the first atoms formed, and the primordial background radiation scattered for the last time. As the radiation cooled, the Universe entered a dark age that would last for half a billion years. Eventually, the first stars, or the first quasars re-lit the Universe with optical and ultraviolet radiation.

Whether the Universe was illuminated first by stars or by quasars is still unknown. However, what has become clear in the last decade is that these two sources of radiation are intimately linked within the galaxies that host them. Quasars are extremely luminous, compact sources of radiation found at the centres of galaxies. They derive their power from the accretion of surrounding material onto a massive ($>10^6 M_\odot$) black hole. Stars, on the other hand, are powered by nuclear fusion, e.g. of hydrogen into helium, in their cores. The two processes, accretion and nuclear fusion, have been responsible for almost all of the energy that has been generated and radiated since the first atoms formed.

In this paper, I will discuss the value of ESA’s future Far InfraRed Mission (FIRM) for understanding the relationship between stars and quasars. I will begin by outlining our basic understanding of the evolution of the stellar and black hole components of galaxies.

2. The evolution of black holes and stars

There is now overwhelming evidence that the creation and fuelling of quasars is related to galaxy formation. The quasar population has evolved strongly with cosmic epoch, declining dramatically since its heyday at redshift $\sim 2$ (e.g. Page et al. 1997, Croom et al. 2004). Data from a variety of sources suggest that star formation also peaked at redshift 1–2 (Bunker et al. 2004, Blain et al. 1999 and references therein). These redshifts correspond to the epoch at which galaxies are expected to have assembled according to the hierarchical cold dark matter cosmology (Kauffmann 1996). The discovery of massive dark objects, remnants of once-luminous quasars in the bulges of many nearby galaxies, further demonstrates that the creation and fuelling of quasars is inextricably linked to the formation of galaxies (Magorrian et al. 1998). Present day massive, quiescent black holes are found to have mass roughly proportional to that of the surrounding galaxy spheroid (Merritt & Ferrarese 2001).

The simplest scenario one can imagine to produce such coupled stellar and black hole components in present-day galaxies is for the stellar bulge and the massive black hole to grow at the same time, from the same gas. In this scenario we would expect quasars, which are black holes that are growing quickly, to be hosted by stellar bulges that are rapidly growing their stellar mass, and are therefore experiencing episodes of prodigious star formation. However, recent observations show that the relationship between star formation and black hole growth is more complex than this. I will return to this question in Sections 5 and 6. First, I will describe briefly the use of X-ray ob-
servations to identify quasars, and the use of far infrared observations to measure star formation.

3. Searching for quasars

Material accreted by a quasar reaches a large velocity as it falls into the gravitational well of the black hole, and forms a disc where some of the kinetic energy is thermalised and radiated. Much of this energy emerges in the extreme ultraviolet region of the spectrum, but it cannot be observed because of photoelectric absorption by interstellar hydrogen in our Galaxy. Close to the event horizon of the black hole, particles are accelerated to very high temperatures, and inverse-Compton scatter radiation from the disc, forming an X-ray emitting corona. This X-ray emission accounts for $\sim 10\%$ of the bolometric output of a typical quasar, a much larger fraction than is emitted in X-rays by normal stars and galaxies. Furthermore, as X-rays are very penetrating, they allow us to find quasars even when they are quite heavily obscured by gas and dust.

Surveys of the X-ray sky therefore prove to be an extremely good (probably the best) method of locating and identifying quasars. It turns out that the vast majority of sources that are detected in X-ray surveys are quasars (e.g. Fig. 1).

Figure 1. XMM-Newton image of the 19H deep field, a 30 arcminute diameter region of sky which has very little intervening Galactic material. Almost all the X-ray sources in the image are quasars.

4. Searching for star formation

In star forming regions massive, short lived stars usually dominate the overall radiative output. These stars emit most of their power in the rest-frame ultraviolet, and so starburst galaxies are often identifiable by their strong ultraviolet emission. However, the most vigorous starburst galaxies are often so dusty that only a tiny fraction of their ultraviolet radiation manages to escape. The spectral energy distribution of one such galaxy, Arp 220, is shown in Fig. 2. In this case, almost all of the energy emerges in the infrared part of the spectrum, between 20 and 200$\mu$m. It would be impossible to determine the energy output of this galaxy without measurements spanning the far infrared part of the spectrum. The spectral energy distribution of Arp 220 is thought to be fairly typical for the most powerful starburst galaxies, and so surveys in the far infrared provide the most reliable means of finding and identifying starburst galaxies.

Figure 2. Spectral energy distribution of the luminous starburst galaxy Arp 220. The spectrum is plotted as the product of wavelength ($\lambda$) and the flux per unit wavelength ($F_{\lambda}$) so that constant energy per decade in wavelength would be a horizontal line. The energy output is completely dominated by the thermal dust emission between 20 and 200$\mu$m (shaded).

5. Star formation in quasar host galaxies

In total we expect the accreting black hole to emit about 1/5 as much energy as the stars forming in the surrounding galaxy spheroid. A far greater mass of gas is converted into stars, but accretion onto a black hole is a much more efficient means of producing radiation than nuclear fusion. Detecting the optical and ultraviolet radiation from the host galaxies of distant quasars is extremely challenging, because the quasar dominates the radiation in these wavebands. However, powerful star forming regions al-
most always contain large quantities of dust, which absorb much of the starlight. Most of the energy is re-emitted as thermal radiation in the far-infrared. Observations at long wavelengths can therefore reveal major bursts of star formation from their strong dust emission. In recent years some such observations have become feasible from the ground, exploiting the atmospheric transmission windows between 350\,µm and 1.1\,mm.

Pioneering millimetre and submillimetre observations of the most powerful quasars, at very high redshift (\(z > 3\)), suggested that high star formation rates may be an ubiquitous characteristic of quasar host galaxies (McMahon et al. 1994, Omont et al. 1996, Isaak et al. 2003). However, if we look at the distribution of quasar luminosities (their ‘luminosity function’) over a range of cosmic time, it is straightforward to determine the luminosity range, and the period of cosmic history, that contributed the most to present day black hole mass. The luminosity function has a distinctive knee or break in its shape at a luminosity which changes with cosmic time (Page et al. 1997, Croom et al. 2004). At luminosities higher than this knee, quasars drop rapidly in numbers, so that the most powerful objects are exceedingly rare compared to their lower luminosity cousins. At luminosities lower than the knee, quasars are more numerous, but not by a large amount. The contribution of any part of the luminosity function to the growth of black hole mass is proportional to product of the numbers and luminosities of the objects. This product is a maximum at the knee of the luminosity function, and \(\sim 70\%\) of the instantaneous black hole mass growth rate comes from \(\pm 0.7\) dex of the break.

The quasar population has changed dramatically with cosmic time, peaking in the \(1 < z < 3\) epoch, when the typical luminosity of a quasar was \(\sim 20\) times larger than it is in the present day Universe. Therefore in terms of contribution to the present day mass density of black holes, the most important quasars by far are those in the redshift interval \(1 < z < 3\), with luminosities around the break in the luminosity function.

Submillimetre observations of quasars in this luminosity and redshift range rule out the simple co-evolution models because the quasars that are responsible for most of the black hole growth are undetectable in the submillimetre. This means that they cannot be undergoing star formation episodes of sufficient magnitude for the spheroid to build up most of its mass in the same timespan as the black hole (Page et al. 2004).

However, quasars at similar redshifts and luminosities, with normal quasar spectra in the optical and UV, but with significant absorption in their X-ray spectra, are found to be luminous submillimetre sources, undergoing major bursts of star formation (Page et al. 2001). This suggests an evolutionary sequence in which X-ray absorbed quasars are at an earlier stage in their evolution than the unabsorbed quasars, in line with a number of theoretical models (Fabian 1999, Hopkins et al. 2005). The luminosities of the X-ray absorbed quasars imply that they have already built up a significant fraction of their ultimate black hole mass – both the X-ray absorbed and unabsorbed quasar phases are relatively late in the active quasars lifetime. The relative numbers of X-ray absorbed and X-ray unabsorbed quasars suggest that the X-ray absorbed phase is short, marking the transition from an earlier heavily obscured phase to the emergence of a luminous, naked quasar. When the quasar runs out of fuel, it ceases to shine, leaving an elliptical galaxy with a quiescent massive black hole in the centre.

6. Black hole growth in starburst galaxies

In the last 10 years, ground based surveys at submillimetre wavelengths have revealed a remarkable population of ultraluminous starburst galaxies, found at high redshift (Smail, Ivison & Blain 1997, Hughes et al., 1998, Barger et al. 1998). These objects are thought to be massive galaxies undergoing their major episodes of star forma-
tion (Smail et al. 2002). Recently, using the deepest X-ray observations ever taken, it has been possible to show that the majority of these objects contain active accreting black holes at their centres, often obscured behind large column densities (> 10^{23} \text{cm}^{-2}) of gas and dust (Alexander et al. 2005). The black holes in these objects appear to be a factor of a few less massive and less luminous than the quasars around the break in the luminosity function, placing them earlier in the quasar evolutionary sequence. Nevertheless, with black holes of 10^{7} M_{\odot} and larger, these objects are already most of the way through their major black hole growth phases.

If we put together the observations of star formation in quasars, and of black hole accretion in powerful starburst galaxies, we come to the following picture:

- Submillimetre galaxies, X-ray absorbed quasars, X-ray unabsorbed quasars and elliptical galaxies appear to form an evolutionary sequence.
- So far, we have only observed (or at least recognised) the last ∼30% of the quasar lifespan.
- Absorption increases as we look further back in the sequence; the black hole is likely to be very heavily obscured for the majority of its main growth phase.

This picture has several implications for our way forward. As we look earlier in the history of a galaxy, the black hole gets more heavily buried in gas and dust, so we need a more powerful X-ray telescope to be able to see through the murk to the earlier stages of black hole growth. Most of the accretion power will be absorbed by the surrounding gas and dust, and will be reradiated in the infrared, but the galaxy will already be a bright source of infrared emission because of the intense dust-enshrouded star-formation that will be taking place. We can only disentangle the infrared quasar emission from the infrared starburst emission using spatial resolution or detailed spectroscopy. Therefore we will need a far-infrared observatory with very fine spatial resolution, excellent spectroscopic sensitivity, or both. The Far InfraRed Mission (FIRM) identified in ESA’s Cosmic Visions programme, fits the bill exactly.

7. Quasars and the growth of structure

In the currently favoured hierarchical cosmology, galaxy formation is a consequence of the gravitational collapse of positive fluctuations in the large scale density field. Small, galaxy-sized structures form first. Larger scale overdensities grow with time, drawing in matter from their surroundings, ultimately producing the filamentary “soap bubble” distribution seen in present day galaxies (Peacock et al. 2001). As the large scale structure develops, small galaxies merge to form larger galaxies, experiencing substantial bouts of star formation in the process; further mergers produce successively larger galaxies. The most massive galaxies end up in the most overdense regions; those which are destined to become clusters of galaxies by the present day.

The black holes that once shone as powerful quasars now lie in the hearts of massive elliptical galaxies, which in turn lie in clusters. By searching for merger-induced starbursts within the environments of redshift ∼ 2 quasars, we can examine how the growth and evolution of massive black holes relate to the build up of large scale structure. At present, with ground based observations, we can probe only the most luminous starbursts in the most massive galaxies. A 450µm image of the environment of the X-ray absorbed quasar RXJ094144 (Stevens et al. 2004) is shown in Fig. 4. The image reveals a chain of ultraluminous infrared galaxies around the quasar, with enough star formation taking place for each starburst to evolve into a massive elliptical galaxy within 1 Gyr. In this case, the X-ray absorbed phase of the quasar coincides with the formation of the massive cluster galaxies. However, to measure the dust emission and star formation rates of the many smaller galaxies that will ultimately lie within the cluster will require much more sensitive observations, at much higher spatial resolution. Indeed most black holes lie in lower mass galaxies, and these within groups rather than clusters of galaxies (our own Milky Way for example, lies within a group of galaxies). With FIRM, we will be able to probe energy production and star formation in these numerous galaxies, and determine how the growth of black holes relates to the build up of structure in these smaller, more typical environments.

Figure 4. 450µm image of a 2.5 arcminute region around the X-ray absorbed quasar RXJ094144 (Stevens et al. 2004), revealing a chain of ultraluminous starburst galaxies. The X-ray position of the quasar is marked by the cross in the centre of the image.
8. A step into the far-IR with Herschel.

The Herschel Space Observatory (Pilbratt 2003) will probe the Universe in the 60–600 $\mu$m region. Due to launch in late 2007, with both spectroscopic and imaging instruments, it will represent a huge advance in this part of the spectrum. With its deep extragalactic surveys, it is set to measure the star formation for a large portion of cosmic history, and resolve a significant fraction of the far infrared background into discrete sources. Figure 5 shows the anticipated coverage of a 5-tier “wedding cake” survey\(^1\) at 250$\mu$m. Herschel should perform extremely well in detecting luminous infrared galaxies in the wavelength ranges where the bulk of their bolometric power is emitted, out to redshifts of 2–3. This corresponds to a large period of cosmic history (> 10 Gyr), but for the majority of this period star formation has been declining. Similarly, accretion onto massive black holes has been waning continuously since redshift 2; the powerful quasars are past their prime, and each successive generation is less luminous than the last.

An earlier epoch, between 1 and 3 Gyrs after the big bang, is a much more exciting period in the story of black hole growth. Star formation was becoming more vigorous with time, and the massive black holes of the most powerful quasars were growing exponentially, limited only by the radiation pressure from their own central engines. From this period of black-hole gluttony emerged the massive compact objects that today lurk at the centres of the greatest elliptical galaxies. Unfortunately, it can be seen in Fig. 5 that Herschel will only detect a small number of objects at the tail-end of this epoch. Principally, Herschel is limited by the angular resolution that is achievable with its 3.5m primary mirror: source confusion will make it impossible to detect the weaker, high redshift objects against the large sky density of brighter, foreground sources. If we are to study the epoch of black hole growth, we will require a more sensitive far-infrared observatory, with much better angular resolution: FIRM.

9. Chicken or egg at redshift 20?

Which came first, stars or black holes? How did the first black holes come about? Did the first stars become the first black holes, seeds around which whole galaxies of stars would ultimately form? These are arguably the most fundamental of questions about massive black holes, and to answer them we will have to make observations stretching right back into the dark ages of the Universe, before reionisation.

The initial results from the WMAP satellite suggest that reionisation occurred at redshift $z = 17 \pm 5$ (Bennett et al. 2003), so the first stars and/or black holes must have formed at $z \sim 20$. Not yet polluted by metals synthesised in stars, the primordial gas would have consisted almost entirely of hydrogen and helium. The first collapsing gas clouds must therefore have cooled primarily through molecular hydrogen ($H_2$) line emission. These emission lines are the key to identifying the first epoch of star formation. The strongest lines predicted have rest frame wavelengths of 2–3 and 8–10$\mu$m (Mizusawa, Nishi & Omukai 2004, Ripamonti et al. 2002, Kamaya & Silk 2002). Although the highest instantaneous luminosities are reached in the 2–3$\mu$m lines during the main accretion phases of individual protostars, the 8–10$\mu$m lines are longer lived, and therefore more likely to be detected from an assembly of star forming clouds. At redshifts of 15–20, the strongest lines will be observed at 130–200$\mu$m: only with a facility such as FIRM can we hope to detect these lines and determine the time when the first stars formed.

Figure 5. Simulated coverage of the luminosity-redshift plane for a 5-tier “wedding-cake” Herschel-Spire survey at 250$\mu$m, similar to the surveys that are currently being planned. Each dot corresponds to an individual galaxy; the individual layers of the cake (flux-limit/sky area combinations) produce the 5 stripes of objects on the diagram. Cosmic time is indicated at the top of the plot. The solid curve shows the position of the knee of the far infrared luminosity function as a function of redshift. On the left hand side of the plot, where the Herschel surveys are effective, the star formation density is declining with cosmic time. FIRM will be required to probe the right hand side of the plot, where the energy output from star formation is still increasing with cosmic time.

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\(^{1}\) A survey with five different sky-area/flux limit combinations, designed to provide good sampling of redshift-luminosity space.
could form directly within primordial gas clouds. The latter possibility requires the suppression of H₂ within the cloud, perhaps due to UV radiation from the first stars (Bromm & Loeb 2003). Such clouds could be identified by the amount of atomic H I cooling relative to H₂ emission. FIRM observations will thus be key to timing and identifying the formation of the first black holes relative to the formation of the first stars.

10. What do we need FIRM to be?

If we are to use FIRM to explore the origin, birth and growth of massive black holes, we can identify the most basic requirements as follows:

- It must provide sensitive spectroscopy in the far infrared (25-300µm) wavelength range.
- It must be in space.
- It must have a cold aperture.
- It must have high enough spatial resolution that it is not confusion limited.
- It could be a large (>10m) single dish.
- It could be a multi-element interferometer.

The most important decision to be taken, for the shape and capabilities of FIRM, is whether to fly a single dish, or a multi-spacecraft interferometer. At present both options are being considered. A single dish would have superior surface brightness sensitivity, but the interferometer wins out in spatial resolution. The two configurations present different technical challenges, and these will have to be taken into account along with the scientific trade-offs when the decision is made.

11. XEUS and FIRM as partners

Quasars are multiwavelength phenomena, emitting throughout the electromagnetic spectrum, and our current understanding of them is the result of observations in every waveband. In the 2015–2025 timeframe, FIRM will be operating alongside a number of exceptionally capable ground-based facilities covering a wide range of wavelengths, including the Atacama Large Millimetre Array (ALMA), the Square Kilometre Array (SKA) and extremely large (100m) optical/near-IR telescopes such as the European Southern Observatory’s OWL telescope. In addition, the gravitational wave observatory LISA may be making a significant contribution to our understanding of black hole growth via an entirely different form of radiation.

However, for the study of the birth and growth of massive black holes, it is in conjunction with ESA’s next generation X-ray observatory XEUS that FIRM has the greatest potential. The very large throughput of XEUS will enable it to detect small, young quasars even when they are embedded in very dense cocoons of gas and dust. Most of their radiation will be absorbed and re-emitted by the surrounding material, and it is FIRM that will detect this radiation, so telling us the total energy budgets of these quasars. FIRM will measure the bolometric output from star formation in their host galaxies, telling us the relative evolution of the black hole and the stellar components. The cryogenic spectrometers on XEUS will identify outflows and winds from young quasars, that may terminate the star formation by sweeping the cool gas from the host galaxy. FIRM spectroscopy will provide the other half of the picture, by revealing the mass, temperature, ionization state and dynamics of this cool gas.

As large scale structures developed, hot gas filled the potential wells of clusters and groups that hosted powerful quasars. XEUS will detect this intracluster medium, and will allow us to measure the conditions and elemental abundances of the gas built up. With FIRM we will learn when, and how this relates to the star formation in the galaxies of the cluster. FIRM will tell us the abundances and physical conditions of cool gas within the galaxies so that we can follow the enrichment history of the intracluster gas. The combination of XEUS and FIRM will allow us to determine the role of feedback from both quasars and starbursts in galaxy formation, and in the heating of the intergalactic medium.

12. Conclusions

In all directions X-ray telescopes reveal massive black holes at great distances, in an earlier epoch, when they accreted material and shone as quasars. In the present day Universe, these black holes lie silent in the centres of galaxies, with mass proportional to that of their surrounding spheroids. This is most easily explained if the formation of the two components was coeval, i.e. if the black hole was built up by accretion of the same gas that rapidly formed the stars of the spheroid. However, the picture is more complex observationally: quasars which had redshifts and luminosities in the interval responsible for most of today’s black hole mass lived, for the most part, in quiescent, finished host galaxies. The formation of the spheroid appeared to overlap the growth of the black hole only in quasars which were hidden within cocoons of gas and dust, with absorption increasing as we look to earlier times in the growth of the black hole. Most of the black hole growth phase was probably heavily obscured, suggesting that we have so far observed and recognised only the final 30% of the evolutionary sequence of a typical quasar.

To detect quasars in the earlier stages of their lives, we need a more powerful X-ray telescope, XEUS, which can penetrate the dense gas and dust in which they are buried. However to get the complete picture, we will also require the Far InfraRed mission (FIRM). FIRM will have a combination of sensitivity and spatial resolution that will allow it to survey the Universe when the first galaxies were taking shape, when quasars were still a vigorously rising...
population, and before star formation reached its peak. Where XEUS will detect the transmitted radiation from youthful quasars, FIRM will measure the energy which has been absorbed and re-emitted in the surrounding screens of gas and dust; thus we will learn the total energy budgets of young quasars. FIRM will measure the bolometric output from star formation surrounding these quasars, to reveal how and when the obscured growth of massive black holes took place relative to the build up of the stars of their host galaxies. Finally, FIRM will detect star formation in their immediate proto-cluster environments and thereby tell us how the formation of the first galaxies and quasars coupled to the earliest large scale structures.

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