The Mid- and Far-Infrared View on Galaxy Evolution

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ABSTRACT

This review provides a summary of spectroscopic diagnostics in the mid- and far-infrared which are relevant for the study of galaxy evolution with *SPICA*. It starts with a description of (some of) the contemporary subjects that have to be addressed for a comprehensive study of this topic. Subsequently, relevant tools are introduced and their application demonstrated with previous results. This review does not aim at being complete in any sense, but is meant as an introduction to the galaxy evolution part of these proceedings, and wants to highlight the tremendous potential for future progress in this area with *SPICA*, in particular with its mid-and far-infrared spectrometers MCS and SAFARI.

1. THE KEY QUESTIONS IN GALAXY EVOLUTION

The baryonic lifecycle of galaxies is determined by a balance between three rates: (1) the inflow rate of baryons through filaments of the cosmic web or galaxy mergers; (2) the rate at which stars form out of cooled gas; and (3) the outflow rate of material, blown out by supernovae, or radiation pressure from young stars or AGNs. Temporary imbalances between these three forces will cause a reduction or increase of its internal gas reservoir. The galaxy and its halo accumulate more mass over time, which leads to structural growth of the AGN and stellar component. Eventually, bulges emerge as galaxies mature, and depart from their star-forming steady state to join the quiescent population.

This is the simplified, qualitative picture of galaxy evolution that has emerged in recent years. A complete and quantitative understanding of the cosmic history of galaxy formation and evolution, however, requires to address a large number of questions and to overcome an almost discouraging amount of problems. Yet, for the purpose of this review it shall suffice to take a very simplistic point of view: if we can answer the following three questions we are pretty much done:

- How many galaxies exist at which redshifts?
- What kind of galaxies are they? E.g. what is the relative importance of star formation and AGN, gas and stellar masses, star formation rates, dust content, black hole masses and accretion rates, etc.
- How did they form their stars and black holes, and how did they evolve into today's population?

In the following I will address various aspects that are directly related to these questions, such as galaxy counts and luminosity functions, the cosmic star formation history, the main sequence of galaxy evolution, the co-evolution of SMBHs and host galaxies, feedback, the different modes of star formation, metallicity evolution, the role of H_2, or the role of clustering and environment.

2. DETERMINING THE COSMIC STAR FORMATION HISTORY

A natural first goal is to get a complete census of the star formation history of galaxies over the entire age (or most of it) of the Universe. While the COB (cosmic optical background) measures the light directly emitted by stars and unobscured AGN, a significant fraction (~50%) of the integrated light of the Universe would be missed by using only (redshifted) UV light as a tracer of star formation. For a complete picture the dust-obscured star formation has to be measured from the CIB (cosmic infrared background). The necessary infrared studies can be sorted roughly in a sequence of four steps:

- How many galaxies are there at which redshifts? Resolve the far infrared background into discrete sources
- determine redshifts and luminosities
- identify (hidden) AGN contribution to these sources and quantify its role
- identify (hidden) star formation contribution and quantify its role

By the time *SPICA* will be launched, the deep cosmological surveys undertaken in the past by *ISO*, *AKARI* and *Spitzer* and with *Herschel* (e.g. Berta et al. 2010; Gruppioni et al. 2010; Eales et al. 2010; Clements et al. 2010, 2011; Lutz et al. 2011; Oliver et al. 2012) will have produced catalogues containing the fluxes of many tens of thousands of faint MIR/FIR/submm sources. It is clear that the statistical census provided by deep look-back surveys has played and will play an important role in establishing the broad scope of the "equilibrium-growth-model" for galaxies described above. See the contributions by Lutz et al., Goto et al., and related posters elsewhere in these proceedings. However, many important elements of such a model require information that only spectroscopy can provide.

Substantial progress in studying galaxy evolution can therefore only be achieved by following up on the photometric surveys with mid- to far-IR spectroscopic surveys, which will identify AGN, provide measured (rather than estimated) redshifts and also unambiguously characterize the detected sources, by measuring the AGN and starburst contributions to their bolometric luminosities over a wide range of cosmological epochs and by allowing various kinds of modeling. *SPICA* will enable us to do for the first time *spectroscopic deep surveys* and, hence, to match the deep imaging surveys with such spectroscopic information. In the following I will briefly recap the mid- and far-infrared spectroscopy toolbox for these purposes.

3. THE MID-/FAR-INFRARED TOOLBOX

3.1. Identifying AGN, and Quantifying SFR and AGN Contribution

The fine-structure atomic and ionic lines accessible with *SPICA* cover a large range in critical density and ionisation potential and thus trace out a wide range of different physical-excitation conditions (e.g. Spinoglio & Malkan 1992). These transitions constrain a wide range of physical conditions and phases of the ISM, from the neutral molecular and atomic ISM, through the ionized ISM (as seen in photo-dissociation regions and H II regions) to the highly ionized AGN and "coronal" regions. These features do not suffer the heavy extinction that affects the UV, optical and even the near-IR lines, and therefore provide an almost unique insight into highly obscured regions. In the mid-infrared *ISO* demonstrated that emission lines tracing the hard UV field found in the narrow line region of AGN (e.g., [Ne V], [O IV], [Ne VI]) are excellent tools to unambiguously identify the presence of an AGN. Their line strengths relative to lines tracing stellar H II regions (e.g., [S III], [Ne II]) can be used to quantify the relative contributions of AGN and star formation to the combined light of their galaxies (e.g. Genzel et al. 1998). But also the weakness or absence of mid-IR PAH, dust, or ice features as well as a strong warm continuum component (peaking in the 10–20 μm range) are good tracers of AGN activity. *Spitzer* observations have refined and extended these methods and enabled the calibration of the line and dust feature luminosities relative to the bolometric luminosities of dusty galaxies (Dale et al. 2006; Desai et al. 2007; Armus et al. 2007; Veilleux et al. 2009; Tommasin et al. 2010). Spectral decomposition methods which try to fit the mid- to far-IR SED with a combination of different template SEDs have also been successful in identifying and quantifying the various components (e.g. Marshall et al. 2007; Schweitzer et al. 2008; Veilleux et al. 2009). PAH and ice features have been applied to *Spitzer* and *AKARI* observations to characterize infrared bright galaxies such as ULIRGs and SMGs in the local Universe as well as out to $z \sim 3$ (e.g. Valiante et al. 2007; Spoon et al. 2007; Pope et al. 2008; Menéndez-Delmestre et al. 2009; Imanishi et al. 2010).

3.2. Further Characterizing the AGN

Hot and young stars as well as black hole accretion discs show strong differences in the shape of their primary ionizing continuum. However the far-UV continuum, dominating the total bolometric output luminosity in both processes, is in general not observable directly, due to absorption by H I and, at longer wavelengths, by dust. In both starbursts and AGN a fraction of the ionizing continuum is absorbed by gas and then re-radiated as line emission. As described above, emission lines ratios from the photoionized gas are, hence, the best tracers and discriminators of accretion and star formation processes (see, e.g., Osterbrock & Ferland 2006). Photoionization models can be used to reconstruct the ionizing UV continuum and hence to further constrain the properties of the AGN (e.g. Alexander et al. 1999, 2000; Spinoglio et al. 2000; Sturm et al. 2002). Dasyra et al. (2011) presented a calibration of the (luminosity-corrected) line widths of highly ionized mid-IR lines to the masses of the central SMBHs.

In the far-IR high-J rotational transitions of CO, together with ionized molecules like H_2O^+ and OH^+, are a promising new tool to help identifying the X-ray dominated regions (XDRs) around AGNs. XDRs are mostly heated by direct photoionisation of the gas, which produces fast electrons that lose energy through collisions with the gas. In contrast, the dominant heating mechanism at the edge of the typical photodissociation regions (PDRs) in star forming regions is photo-electric heating: FUV photons are absorbed by dust grains, which release electrons that lose their surplus kinetic energy to the gas by Coulomb interactions. The impact of X-rays on the ISM is therefore different from UV photons. In the recent past models have become available (e.g. Meijerink et al. 2007; Schleicher et al. 2010) which can be used to predict the strength of high-J CO lines in the FIR and to distinguish between XDRs and PDRs. With the *Herschel Space Observatory* it has become possible for the first time to observe these CO lines.

However, observationally there is a lot of scatter, and cosmic rays and shocks have to be considered as excitation mechanisms, too. Therefore a good sampling of the CO line SED up to really high-J (e.g. $J = 40$ at 65 μm) is needed (and expansion of the models). Hailey-Dunsheath et al. (2012) have demonstrated both the power and the caveats of this new tool on the example of the archetypical Seyfert 2 galaxy NGC1068. Full line SEDs will be hard to observe with ground based observatories like ALMA and NOEMA. An alternative solution could be ratio-ratio diagrammes invoking just a few transitions at strategic J levels. For instance diagrammes using CO(18–17)/CO(1–0) vs. CO(6–5)/CO(1–0), which trace very warm components ($J = 18$), the peak of normal star forming galaxies ($J \sim 6$) and the cold component ($J = 0$), must be explored more both observationally and theoretically. First attempts at this (Mashian et al. in prep.) are promising. As mentioned above, interpretation of high-z high-J CO lines with, e.g., CCAT, NOEMA, or ALMA will not be straight forward. *Herschel* has allowed first observations, but only *SPICA* can help to calibrate and fine tune this new tool fully in the local universe.

SPICA will for the first time enable the kind of mid- and far-IR emission line studies described above — i.e. direct identification of AGN in dusty galaxies, quantifying the role of SF and AGN, and determining the physical properties of the ISM and AGN — at redshifts around the peak of the cosmic star and SMBH formation history ($z = 1.3$, and beyond using PAH features).

4. CO-EVOLUTION AND FEEDBACK

A well known correlation between the mass of galaxy spheroidal components and super-massive black holes (SMBH Ferrarese & Merritt 2000) strongly suggests that star-formation in galaxies (several kpc scale) and SMBH mass growth (<pc scale, the so-called AGN activity) are closely linked, and that galaxies and SMBHs have co-evolved. Both star-formation and AGN activity went through an accretion phase in the early universe, show peaks at $z \sim$1–2, and have been winding down towards $z = 0$. Whether or not this co-evolution is reflecting a direct physical link is a major subject of current astronomy. Possible controlling mechanisms providing positive feedback are common feeding (e.g. in mergers), 'secular' disk instabilities and clumps, bars, nuclear spiral structures, or triggered star formation through winds/shocks from AGN and/or stars. On the other hand, negative feedback could come from the quenching of star formation and starvation of BHs via strong (e.g. radiation pressure driven) winds/outflows from AGN and/or stars.

In particular the winding down phase is hard to explain without some kind of negative feedback mechanisms. Something must have stopped the growth of both galaxies and SMBHs around the same time at $z \sim 1$, otherwise there would be more massive galaxies today than we observe. In order to reproduce this winding down behaviour quantitatively many galaxy evolution models include some kind of negative feedback mechanism that would quench both star formation and AGN growth. Somehow the steady accretion of material or the enhanced inflow during a merger has to be stopped, if not removed entirely. A prime candidate for this is negative feedback from the AGN: once an AGN has grown powerful its winds and/or radiation pressure are supposed to blow away the gas that is feeding the SMBH as well as the star formation around it. Galactic winds have been known for a long time, but mostly in ionized or neutral atomic gas. Stars are formed from cold molecular gas, however. Hence, in order to witness the quenching process in action, we have to observe outflows in molecular gas. Recent observations with *Herschel*-PACS have allowed exactly this: the detection of strong molecular outflows, as traced by P-Cygni profiles or blue shifted absorption of OH, in ~60 local ULIRGs and QSOs (Fischer et al. 2010; Sturm et al. 2011; Veilleux et al. 2013; Spoon et al. 2013). These observations show a correlation of the outflow velocity with AGN luminosity, with maximum velocities reaching well above 1000 km/s in the most luminous AGN-ULIRGs. Sturm et al. (2011) have modeled the outflows in a handful of objects applying radiative transfer models. They find mass loss rates of up to 1000 $M_\odot$/yr, mass loading factors (mass loss rate/star formation rate) of up to ~10, momentum fluxes ($dM/dt \times v$) reaching $\sim 10L(\mathrm{AGN})/c$, and mechanical luminosities ($dM/dt \times v^2$) of a few per cent of $L(\mathrm{AGN})$. These values strongly suggest that radiation pressure from the AGN is the main driver of these outflows (e.g. Debuhr et al. 2012), in line with the high velocities and correlation of velocities with $L(\mathrm{AGN})$. *SPICA* will be able to trace molecular outflows, and therefore to probe a key feedback mechanism, at the peak epoch of cosmic evolution (using OH transitions below rest wavelengths of 100 μm).

The mid-IR range provides a large number of tools to address the issue of co-evolution in various ways. E.g. the star formation in the hosts of QSOs can be studied via PAH features and other star formation tracers like [Ne II] (Schweitzer et al. 2006; Lutz et al. 2008). The construction of luminosity functions from high ionization lines like [O IV] can be used as a means of studying the accretion rate history of the Universe that is an alternative to X-rays, in particular for Compton thick sources. The widths of the same lines depend on the kinematics of the clouds that they probe, determined by either the gravitational potential out to a radius that the AGN luminosity dictates, or by AGN feedback effects. They can be used to weigh the masses of black holes, permitting the creation of black hole mass functions that include obscured AGN with SAFARI out to redshift of ~4 using the [O IV] line.

5. THE MAIN SEQUENCE AND DIFFERENT MODES OF STAR FORMATION

The rate at which galaxies produce new stars is proportional to the amount of stellar mass they already assembled. This relation is known as the main sequence of star formation, on which ~98% of star forming galaxies reside. The tight locus defined by the vast majority of star forming galaxies in this $M_\star$–SFR plane is dominated by disk-like systems while rarer "outliers" above and below this "main sequence" show more compact, cuspier morphologies (Wuyts et al. 2011). Resolved measurements of the kinematics and structure of high-z galaxies provided key evidence that smoother accretion and internal dynamical processes play a dominant role in growing galaxies, rather than violent major mergers that had been favored for some time. In other words, most star formation happens near the main sequence, in a rather steady way (and fed from the cosmic web/minor mergers rather than major mergers). This main sequence is observed at all wavelengths, but with some evolution: at a given stellar mass, galaxies on this sequence were forming stars at much higher rates in the distant universe relative to today (e.g. Brinchmann et al. 2004; Noeske et al. 2007; Daddi et al. 2007; Elbaz et al. 2007; Peng et al. 2010; Rodighiero et al. 2010; Whitaker et al. 2012), i.e. the specific star formation rate ($SSFR = SFR/M_\star$) decreased from $z = 2$ to $z = 0$. While a galaxy evolves upward on the main sequence, the whole main sequence shifts downwards, i.e. the SFR stays roughly constant over long times. This points towards secular effects: the galaxies have to accrete material steadily over long periods.

Many IR properties of infrared bright galaxies are therefore best described in relation to the evolving main sequence of star forming galaxies, rather than simply by L_{IR} and a (U)LIRG nomenclature: locally, the galaxies with IR luminosities exceeding 10^{12} $L_\odot$ are predominantly associated with mergers of comparable mass spirals. At high z, high IR luminosities can be achieved via galaxy mergers, but as described above smooth, steady accretion of cold gas in cooling flows turns out to be the more important mode: major mergers manifest themselves in the $M_\star$–SFR as "outliers" in a region above the main sequence.

The trend with redshift is consistent with the larger molecular gas fractions of galaxies at earlier epochs. They produce more stars because they have more material for star formation available. However, the SSFR in galaxies (i.e. the position in the SFR–$M_\star$ plane) is not determined by variations in the molecular gas content alone. Also the efficiency to convert this gas into stars (star formation efficiency, SFE) seems to vary. Independent support for the different star-forming relations in normal disk galaxies and major merger systems has come from recent far-IR spectroscopy with *Herschel* (Graciá-Carpio et al. 2011). Galaxies with high L_{FIR}/M_{H2} ratios tend to have weaker fine structure lines relative to their far-infrared continuum than galaxies with "normal" L_{FIR}/M_{H2}. As H_2 is the reservoir for star formation, and L_{FIR} is proportional to the amount of star formation that has already appeared (being UV light from young stars that has been absorbed by dust and re-emitted in the infrared), this ratio can be considered a star formation efficiency. The L_{FIR}/M_{H2} value where these line deficits start to manifest is similar to the limit that separates between the two modes of star formation found in the above mentioned studies of galaxies on the basis of their gas-star formation relations (Genzel et al. 2010; Daddi et al. 2010). In other words, galaxies above the main sequence have a higher SFE, and their ISM, as traced by the line deficiencies, is warmer, denser and more compact (Graciá-Carpio et al. 2011 and in prep.; Díaz-Santos et al. 2013).

The strength of far-IR fine structure lines relative to the L_{FIR}/M_{H2} ratios of their galaxies can therefore be used as a tool to examine the mode of star formation in high redshift galaxies. This has been applied for the first time with *Herschel*-PACS. For instance, Sturm et al. (2010) have analyzed IRAS F10214+4724, a well studied lensed $z = 2.29$ HyLIRG (Sy2) with coeval star formation and AGN activity. This object exhibits a strong O III deficit, which points towards a major merger history. A second object in their study, MIPS J142824.0+352619, is, like F10214, a hyperluminous lensed object at $z = 1.32$, but without AGN signatures. Contrary to F10214, J142824 does not show an O III deficit, i.e. this object has the luminosity of a local ULIRG, but the star formation efficiency of a normal starburst, probably forming stars in a more steady accretion mode. These *Herschel* observations are promising, but were naturally restricted to a handful of the brightest objects. Only *SPICA* will be able to further develop and apply this tool to large numbers of objects at high redshifts and to determine their mode of star formation without the need to determine their stellar masses (and hence their position in the $M_\star$–SFR plane).

6. METALLICITY EVOLUTION

Another important property to distinguish various galaxy evolutionary scenarios is the metallicity of gas and stars in galaxies, since metals reflect the history of both the star-formation activity and the gas inflow and outflow in galaxies.

In the past mostly rest-frame optical emission lines have been generally used to measure the metallicity. To accurately determine the metallicity of dust-obscured galaxies, and accordingly to understand the chemical evolution of dusty populations, mid- and far-infrared tools are needed, which are less affected by extinction. Usually, the strengths of fine structure lines relative to hydrogen recombination lines are used to derive the metallicity of the gas producing these emission features. In practice, however, the hydrogen lines within the mid- to far-IR wavelength range (e.g. Pf α 7.5 μm and Hu α 12.4 μm) are very faint and close to other spectral lines and dust features. In the *ISO* and *Spitzer* era such measurements were difficult (Verma et al. 2003;Bernard-Salas et al. 2009 for starburst galaxies) or could only be done for stacked spectra of large samples (Veilleux et al. 2009 for ULIRGs).

However, thanks to the higher sensitivity and spectral resolution, the medium resolution spectrometer (MRS) of *SPICA*/MCS promises to detect Hu α to at least 10 times fainter limits than *Spitzer*/IRS. Metallicity measurement for star-forming galaxies (including the very dusty populations) can hence be extended out to $z > 1$. Note that *SPICA*/MCS is more powerful in this metallicity study than *JWST*/MIRI at z > 0.6, where Hu α (and the neon emission lines) shift beyond 20 μm.

Nagao et al. (2011) proposed diagnostics of the gas metallicity which does not make use of hydrogen recombination lines but is based on far-infrared fine-structure emission lines, like [O III]52 μm, [O III]88 μm, and [N III]57 μm. These lines are among the brightest fine structure lines and nearly unaffected by dust extinction even in the most obscured systems. Metallicity measurements with these fine-structure lines will be feasible at relatively high redshift (z~1 or more) with *SPICA*, even in galaxies with rather modest star formation rate.

7. THE ROLE OF H_2 AS MAJOR COOLANT IN THE FIRST GALAXIES

How the first stars (population III stars) formed out of primordial gas is one of the most important questions in modern astrophysics. It has long been realized that the gravitational collapse of the primordial clouds must have been induced by H_2 line cooling (e.g. Saslaw & Zipoy 1967). Kamaya & Silk (2002) and Mizusawa et al. (2004) considered the H_2 rotational emission from primordial molecular cloud kernels to be associated with the formation of the first stars at the earliest epochs of $z \sim 20$. Millennium simulations predict how the H_2 mass function has evolved with redshift (Obreschkow & Rawlings 2009). The simulations suggest that a large fraction of galaxies at redshifts 8–10 are expected to have $M(H_2) \sim 10^9$ $M_\odot$. This would correspond to a flux of $H_2S(0)$ of a few 10^{-18} Wm^{-2}, which is within the reach of SAFARI.

Few observations of H_2 at high redshift exist today: it has been detected in stacked spectra of $z \sim 1$ galaxies (Dasyra et al. 2009), in $z \sim 2$ galaxies (Fiolet et al. 2010) and in a highly magnified LIRG behind the Bullet Cluster at $z = 2.79$

(Gonzalez et al. 2010). *Spitzer* observations of $z < 0.3$ radio galaxies (Egami et al. 2006; Ogle et al. 2007, 2010), also unveiled a class of "H_2 luminous galaxies" whose spectra have extremely bright H_2 rotational lines, possibly due to the jet-ISM interaction. Similarly, the H_2 S(1) transition is by far the brightest emission line in the whole 10–35 μm range in Stefan's Quintet (Appleton et al. 2006). The lack of PAH and hydrogen recombination line emission rules out UV fluorescence as a possible excitation mechanism, indicating that H_2 is produced by shocks which deposit large amounts of kinetic energy into the ISM. These H_2 luminous galaxies may represent a population at high redshift where interactions and mergers are more common (see the contribution by P. Appleton to these proceedings).

8. THE ROLE OF CLUSTERING / ENVIRONMENT

Galaxy properties are known to be strong functions of the environment. Hence, the large-scale structure formation in the Universe should play a role in shaping individual galaxies. For instance, high-density environments such as galaxy clusters are dominated by red early-type galaxies with old stellar population, while galaxies in low-density fields are mostly blue late-type galaxies with on-going star formation (e.g. Dressler 1980; Lewis et al. 2002; Gómez et al. 2003). The young "progenitors" of the present-day passive cluster galaxies should therefore be observable as strong dusty starbursts in the distant Universe. An important goal of the *SPICA* mission is therefore to directly detect such dust-obscured star-formation along the young, forming large-scale structures, and to identify the role of environment at the frontier redshift at $z \gg 1$.

A study of the evolution of the Large Scale Structure in the Universe and of the three-dimensional clustering will be a natural "by-product" of large area deep spectroscopic surveys with *SPICA*, which will deliver precise spectroscopic redshifts of thousands of sources out to high redshifts, together with their physical properties. Galaxies observed by *SPICA* surveys will either reside in overdense or underdense regions. This will allow to investigate the impact of environment on galaxy formation and evolution as a function of redshift up – and possibly beyond – the epoch which marks the bulk of AGN/stellar activity. This shall provide answers to a number of questions, such as whether there is any large-scale influence between the surrounding environment and AGN/stellar activity and, if so, if seeds for such a phenomenon were already in place by $z \sim$2–3. Beside the redshift measure, the spectroscopic diagnostics will be essential to measure directly the star formation and AGN luminosities in each cluster component.

Significant clustering has been measured in high-redshift ($z \sim$1–3) *Spitzer* galaxies (Farrah et al. 2006; Magliocchetti & Brüggen 2007; Magliocchetti et al. 2008), with a strength which increases with redshift. Comparisons with theoretical models have provided a direct estimate of the dark matter mass of such sources, and the derived values ($M \approx 10^{13}\ M_\odot$) indicate that luminous IR galaxies at $z \sim 2$ are indeed most likely the progenitors of the giant ellipticals which reside locally in rich clusters, as speculated above. This implies that studies of the IR population at redshifts $z >$1–1.5 provide a unique tool to investigate the formation and evolution of super-structures such as proto-clusters and clusters, from even before the peak time of cosmic star formation activity. While the results from *Spitzer* necessarily suffered from limitations due primarily to the lack of measured redshifts, SAFARI will, for the first time, be able to overcome such problems and provide definite answers to many crucial issues.

9. THE BIG STEP FORWARD WITH *SPICA*

SPICA offers a sensitivity up to two orders of magnitude better than *Herschel*, covering the mid-to-far-IR (the full 5–210 μm range). This major increase in sensitivity, combined with a wide field of view and simultaneous coverage of large wavelength ranges, will allow us to spectroscopically explore the nature of the tens of thousands of objects that *Herschel*, *JWST* (and *SPICA* itself) will discover in photometric surveys or the regions that are too extended to be mapped with ALMA. *SPICA* will have for the first time the spectroscopic capabilities necessary to perform deep spectroscopic surveys, wide and deep enough to measure the underlying physical processes driving galaxy evolution out to high redshifts (see the line strength prediction by Spinoglio et al. (2012) and the contribution by L. Spinoglio to these proceedings). This will be a truly unique big step forward for our understanding of the star and galaxy formation history of the universe.

I would like to the thank the organizers for such a fruitful and pleasant conference. This summary presentation is based on the works of a large number of colleagues, whom I want to express my respect and gratefulness. Yet this overview can only be a rather incomplete, and I apologize to all those ingenious colleagues whose work could not be mentioned here, solely for the lack of space. In preparing this contribution I have benefitted invaluably form the SAFARI Yellow Book and the MCS Science Case Document, and I want to particularly thank the authors of these documents.

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