Galaxy evolution studies with the SPace IR telescope for Cosmology and Astrophysics (SPICA)


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Abstract
IR spectroscopy in the range 12–230 µm with the SPace IR telescope for Cosmology and Astrophysics (SPICA) will have the potential to reveal the physical processes that govern the formation and evolution of galaxies and black holes through cosmic time, bridging the gap between the James Webb Space Telescope (JWST) and the next generation ELTs at shorter wavelengths and ALMA in the submillimeter. SPICA, with its 2.5-m telescope actively-cooled to <8K, will be able to obtain the first spectroscopic determination, in the mid-IR rest-frame, of both the star-formation rate and black hole accretion rate histories of galaxies, reaching lookback times of 12 Gyr, for large statistically significant samples. Densities, temperatures, radiation fields and gas-phase metallicities will be measured in dust-obscured galaxies and active galactic nuclei (AGN), sampling a large range in mass and luminosity, from faint local dwarf galaxies to luminous quasars in the distant Universe. AGN and starburst feedback and feeding mechanisms in distant galaxies will be uncovered through detailed measurements of molecular and atomic line profiles. SPICA’s large-area deep spectrophotometric surveys will provide mid-IR spectra and continuum fluxes for unbiased samples of tens of thousands of galaxies, out to redshifts of z~6. Furthermore, SPICA spectroscopy will have the potential to uncover the most luminous galaxies in the first few hundred million years of the Universe, through their characteristic dust and molecular hydrogen features.

Keywords: galaxies: evolution – galaxies: active – galaxies: starburst – infrared: galaxies – techniques: IR spectroscopy

1 INTRODUCTION

Over the past three decades, we have learned that at least half of the energy ever emitted by stars and accreting black holes in galaxies is absorbed by dust, and re-radiated in the infrared (e.g. Franceschini et al. 2008). We now know that the peak in the growth of galaxies occurs at redshifts of z~1–3 (Lilly et al. 1996; Franceschini et al. 1999; Madau & Dickinson 2014; Rowan-Robinson et al. 2016), when the Universe was roughly 3 Gyr old — a result achieved primarily through deep and wide-field observations with previous IR space observatories, namely the IR Astronomical Satellite (IRAS, Neugebauer et al. 1984), the IR Space Observatory (ISO, Kessler et al. 1996), Spitzer (Werner et al. 2004), AKARI (Murakami et al. 2007), Herschel (Pilbratt et al. 2010) and the Wide-field IR Survey Explorer (WISE, Wright et al. 2010). Despite their successes, these observatories had either small cold telescopes, or large, warm mirrors, ultimately limiting their ability to probe the physics, through spectroscopy and deep photometry, of the faintest and most distant obscured sources in our Universe.

Due to the progress in detector performance and cryogenic cooling technologies, great advances in our ability to study the hidden, dusty Universe can be made through observations in the thermal infrared.
Figure 1. Estimated star-formation rate densities from the far-ultraviolet (FUV, blue points) and far-IR (FIR, red points) photometric surveys (adapted from Madau & Dickinson 2014). The estimated black hole accretion rate density, scaled up by a factor of 3300, is shown for comparison (in green shading from X-rays and light blue from the IR). For redshifts above \( z > 2 \), very little IR data on the SFR exist, making rather poor its determination. The redshift ranges probed with SPICA spectroscopy (up to \( z \approx 4 \)) and photometry (up to \( z \approx 6 \)) are also shown.

The SPace IR telescope for Cosmology and Astrophysics (SPICA, Swinyard et al. 2009; Nakagawa et al. 2014) will achieve a gain of over two orders of magnitude in spectroscopic sensitivity in the mid/far-IR compared to Herschel and Spitzer. SPICA will provide access to wavelengths well beyond those reachable with the James Webb Space Telescope (JWST, Gardner et al. 2006) and the new generation of Extremely Large Telescopes (ELTs), and at wavelengths shortward of those accessible by the Atacama Large Millimeter/Submillimeter Array (ALMA, Wootten & Thompson 2009). It will enable the discovery and detailed study of normal galaxies across their key phases of evolution, as well as probing the earliest forming galaxies and super-massive black holes.

A description of the SPICA mission was originally presented in Swinyard et al. (2009) and recent updates can be found in Nakagawa et al. (2014), Sibthorpe et al. (2016), and in Roelfsema et al. (2017). SPICA will consist of a 2.5m primary mirror, actively cooled to <8K. There are two primary instruments sharing the focal plane: the Far-IR Instrument (SAFARI) and the Mid-IR Instrument (SMI). SAFARI includes the grating spectrometer covering the 34–230\( \mu m \) spectral range simultaneously at a resolution \( R \approx 300 \). The combination of the grating with a Martin-Puplett interferometer allows for observations at higher spectral resolution (1500<\( R <11000 \), depending on wavelength) over the same spectral range. SAFARI also includes the imaging polarimeter POL, with a field of view of 80" \times 80" in three spectral bands centred at 110, 220 and 350\( \mu m \). A description of the SAFARI optical system architecture and design concept is given in Pastor et al. (2016). SMI covers the wavelength range of 12–36\( \mu m \), using three spectroscopic channels: low-resolution (\( R = 50–120, 17–36\mu m \)), mid-resolution (\( R = 1300–2300, 18–36\mu m \)), and high-resolution (\( R = 28000, 12–18\mu m \)). SMI can also obtain large field of view (10′ \times 12′) images at 34\( \mu m \). A full description of the SMI instrument can be found in Kaneda et al. (2016).

This article describes how SPICA will be able to address the study of galaxy formation and evolution, while a companion article focuses on the studies of the ISM in nearby galaxies (van der Tak et al. 2017). It is organised as follows: sect. 2 introduces the current knowledge that has been accumulated so far in studying galaxy evo-
solution and identifies a number of open questions that can be addressed and answered with high sensitivity IR spectroscopic and photometric observations.

We show in sect. 3 how IR spectroscopy is able to separate the two main energy production mechanisms of star formation and black hole accretion along galaxy evolution up to redshift of \( \sim 3-4 \). Finally, sect. 4 illustrates the synergies of the SPICA observations with the current and future facilities at other frequencies and sect. 5 gives the conclusions.

2 The rise and fall of galaxy formation

The bulk of star formation and supermassive black hole accretion in galaxies appears to have taken place more than six billion years ago, dropping sharply towards the present epoch (e.g., Madau & Dickinson 2014, and references therein, see Fig. 1). Since around half of the energy emitted by stars and accreting super-massive black holes is absorbed and re-emitted by dust, understanding the physics of galaxy evolution requires IR observations of large, unbiased samples of galaxies spanning a wide range in luminosity, redshift, environment and nuclear activity. From Spitzer and Herschel photometric surveys the star formation rate (SFR) and black hole accretion rate (BHAR) density functions have been estimated through the bolometric luminosities of galaxies. However, these estimates should be treated with caution, because they are typically based on observations of only a few, broad IR bands, making the IR luminosities and the relative contribution of star formation and black hole accretion, highly uncertain. This crucial separation has been attempted so far through modelling of the spectral energy distributions (SEDs) and relies on model-dependent assumptions and local templates, with large uncertainties and degeneracies. Indeed Spitzer and Herschel based studies have been successful in estimating counts and evolving galaxy luminosity functions (Le Floc’h et al. 2005; Pérez-González et al. 2005; Oliver et al. 2012; Magnelli et al. 2013; Lapi et al. 2011) but only through statistical techniques applied to bulk galactic populations as a function of redshift.

Determinations of the SFR from ultraviolet (UV) and optical spectroscopy are based on measurements of only \( \sim 10\% \) of the total integrated light which escapes through dust absorption. These must therefore be corrected upwards by large, uncertain extinction factors (Fig. 1). X-ray analyses of the BHAR, similarly, are prone to large uncertainties, because deriving the bolometric luminosity from the X-ray luminosity depends on uncertain bolometric corrections (e.g., Vasudevan & Fabian 2009) and on estimates of the Compton-thick population contribution. The IR emission line spectra can be used to physically separate these contributions to the total integrated light on a galaxy-by-galaxy basis, directly measure redshifts, SFRs, BHARs, metallicities and physical properties of gas and dust in galaxies. For SPICA, we will be able to do this for at lookback times up to about 12 Gyrs.

With its large, cold telescope and powerful instruments, SPICA will peer into the dust-enshrouded phases of galactic formation and evolution, revealing the physical, dynamical and chemical states of the gas and dust, and will provide answers to the following questions in galaxy evolution:

1. How does accretion and feedback from star formation and AGN shape galaxy evolution?
2. How are metals and dust produced and destroyed in galaxies? What is the metallicity evolution in galaxies as a function of redshift?
3. How can the early black holes and starbursts towards the epoch of re-ionization be detected and studied?
4. How did primordial gas clouds collapse into the first galaxies and black holes?
5. What are the histories of the star formation and black hole accretion rates through cosmic time and how these two processes drive galaxy evolution?

In the following four sections we briefly address each of the first four questions, reserving detailed analysis of the role of SPICA in answering these to four companion articles: i) the role of feeding and feedback in galaxy evolution (González-Alfonso et al. 2017b); ii) the chemical evolution of galaxies and the rise of metals and dust (Fernández-Ontiveros et al. 2017); iii) dust obscured star-formation and accretion histories from re-ionization using SPICA photometric surveys (Gruppioni et al. 2017) and iv) the first stars and galaxies (Egami et al. 2017). We leave the detailed analysis of the final question to sect. 3.

2.1 AGN Feeding and Feedback in the context of galaxy evolution

The correlations between SMBH masses and their host galaxy properties (Magorrian et al. 1998; Ferrarese & Merritt 2000), and the bimodality of the colour distribution of local galaxies (e.g., Strateva et al. 2001; Baldry et al. 2004), suggest that the growth of BH and stellar mass are related over the lifetime of a galaxy. In other words, feedback between SMBH and galactic star formation may be in part responsible for the \( M_{\text{BH}}-\sigma \) relationship seen in the local Universe (e.g., Silk & Rees 1998; Di Matteo et al. 2005; Springel et al. 2005). It is precisely this feedback on the dense, circum-nuclear ISM that we can study with SPICA in the far-IR. Herschel spectroscopic observations of far-IR OH lines (Fischer et al. 2010; Sturm et al. 2011; González-Alfonso et al. 2014, 2017a) have shown that fast, molecular outflows are common among AGN-powered local
ULIRGs. SPICA spectroscopy will allow us to search for these outflows well beyond the nearest galaxies - reaching up to $z=1-2$, and therefore providing an estimate of the impact of AGN-driven feedback to the peak epoch of star formation. With the SAFARI instrument on SPICA we will be able to detect the spectral signatures of outflowing dense molecular gas (through P-Cygni profiles on the OH 79$\mu$m and 119$\mu$m lines and blue-shifted high velocity wings in the OH 65$\mu$m line) in ULIRGs like Mrk 231 at $z=1.5$ in a few hours of integration. This will allow surveys of hundreds of galaxies at these redshifts, providing a measure of the demographics of molecular feedback in IR-luminous galaxies at the peak of the SFR density.

Far-IR spectroscopy can also provide direct evidence for the feeding of the SMBHs and central starbursts. Inflowing gas can be identified through inverse P-Cygni profiles or redshifted absorption lines of OH and [OI]63$\mu$m, as shown by Herschel (González-Alfonso et al. 2012; Falstad et al. 2015). SPICA will therefore be able to measure the dynamics of the molecular gas in and around the nuclei of rapidly evolving, dusty galaxies and study both AGN accretion and energetic feedback in significant samples of dusty galaxies over the past 10 Gyr. For a more detailed discussion of the capabilities of SPICA to detect galactic feedback, see the companion paper by González-Alfonso et al. (2017b).

2.2 The Rise of Metals and Dust
Galactic evolution is intimately tied to the production of metals and dust. Elements heavier than He (i.e. “metals”) play a major role in gas cooling, allowing cloud collapse and ultimately star and planet formation. The metallicity in galaxies is determined by the cumulative effects of star formation, outflows, accretion and radial redistribution of matter. Traditional metallicity diagnostics, based on optical lines, are biased toward dust-free regions, yielding metallicities significantly lower than those inferred from the dust mass or IR lines (e.g., Santini et al. 2010; Croxall et al. 2013, Pereira-Santaella et al. 2017, submitted). Furthermore, temperature variations within galaxies, which can strongly influence optically derived abundances, have little effect on IR-derived values, which are derived from lines lying close to the ground state (Bernard Salas et al. 2001). IR fine-structure lines provide extinction-free measurements of metallicity of galaxies, nearly independent of ionization, density and temperature out to redshift $z\sim3$. Moreover, SPICA can detect mid-IR Hydrogen recombination lines in galaxies at intermediate redshifts ($z\sim1.5$–2), which, together with the forbidden lines, allow for direct determination of the Ne, S, N, O and Fe abundances.

Dust also plays a critical role in heating and cooling the ISM in galaxies. It forms in the dense, enriched atmospheres of evolved stars, novae, supernovae and dense molecular clouds (Valiante et al. 2009; Zhukovska & Henning 2013; Marassi et al. 2015; Bocchio et al. 2016) and is destroyed by shocks, sputtering and intense radiation fields. However, its dominant formation and destruction channels in different environments are poorly understood (Kemper 2015; Matsura et al. 2011; Micelotta et al. 2016). IR spectroscopy can uniquely measure the dust mass produced by evolved stars and supernovae in nearby galaxies allowing a detailed study of the dust mineralogy and composition, via the mid-IR SiO$_2$, FeO, FeS and crystalline silicate features. SPICA will trace the abundance and evolution of the dust components within galaxies, constraining the local conditions, such as ionization, radiation field, dust structures and overall dust-to-gas ratios, giving us clues to the chemical evolution of galaxies (Sandstrom et al. 2012; Rény-Ruyer et al. 2014). For the details of this study and the assessment of the SPICA observations, we refer to the companion papers by van der Tak et al. (2017); Fernández-Ontiveros et al. (2017), for local and distant galaxies, respectively.

2.3 Towards the Epoch of Re-ionization: early Black Holes and Starbursts
The deepest cosmological surveys with Herschel (e.g., Gruppioni et al. 2013; Magnelli et al. 2013; Lutz 2014; Oliver et al. 2012) mapped out the star-formation rate density to $z\sim3$ for the first time, but detected only small numbers of the most luminous ($L\gtrsim10^{12}$L$_\odot$) star-forming galaxies at $z>3$. High redshift ($z>6$) quasars have been detected containing black holes as massive as $10^{10}$M$_\odot$ (Wu et al. 2015; Jun et al. 2015), but their origin, demographics and role in re-ionization are still unclear. Deep SPICA/SMI photometric surveys will extend the study of the black hole accretion rate and the star-formation rate density well beyond $z\sim3$, detecting, in the rest-frame 34$\mu$m band, the hot dust around high-redshift QSOs, as well as starburst-dominated galaxies at redshifts out to $z\sim6$. Due to its large field of view of 10’ × 12’, SMI will map large sky areas to the confusion limit (around 5$\mu$Jy) in relatively short times, with an effective surveying speed two orders of magnitude faster than JWST. Deep and wide photometric surveys with SPICA allow us to study the build-up of the progenitors of elliptical galaxies dominating local galaxy clusters, and thus to probe environmental-dependent evolution (e.g., Dannerbauer et al. 2014; Clements et al. 2016). For a more detailed description of potential photometric surveys with SPICA, and their role in extending our knowledge of the population of IR-bright galaxies.

\footnote{The JWST Design Reference Mission includes a MIRI (16$\mu$m, 5$\sigma$) 10'×9' survey at 24$\mu$m. With the MIRI field of view of 1.25'×1.88', this survey will need 160 hrs. A similar SMI survey at 34$\mu$m, would take 1 hr (12$\mu$m, 5$\sigma$). For detecting mid-IR sources SPICA will be over 100 times faster than JWST.}
at z>3, see the companion paper by Gruppioni et al. (2017).

2.4 The First Stars and Galaxies

Through chemical enrichment and the production of dust, the earliest stars imprint their signature on the ISM of high-redshift galaxies. The first generation of quiescent, self-contracting metal-poor/free primordial gas clouds may be too faint to be detected directly with SPICA (e.g., Mizusawa et al. 2005; Santoro & Shull 2006; Gong et al. 2013). However, during the hierarchical structure formation process, both the merging of primordial clouds and feedback due to supernovae and stellar winds can produce pockets of shock-heated gas. Molecular clouds can be efficiently formed in the cooling gas behind the shocks (Ferrara 1998; Ciardi & Ferrara 2001) and if these clouds are warm and massive enough, they could be detected with SAFARI through their H$_2$ emission. Such systems of warm massive H$_2$ gas reservoirs are known at lower redshift (Egami et al. 2006; Ogle et al. 2012), and can be detected by SPICA out to $z\sim 10$.

The ultimate challenge for SPICA will be to catch a glimpse of the first (i.e., Pop III) galaxies. Theoretical models predict that Pop III star clusters should produce a large amount of dust quickly, as massive pair instability supernovae (PISNe) explode (e.g., Schneider et al. 2004). When the dust is released and heated by hot, main sequence Pop III stars, the resultant mid-IR spectra exhibit strong quartz (SiO$_2$) emission lines, which SPICA may detect. They will give a rare glimpse into the dust production mechanism of Pop III stars and provide strong constraints for their models. For a detailed discussion of the potential for SPICA to detect the cooling signatures of young, luminous galaxies at high redshift, see the companion paper by Egami et al. (2017).

3 Infrared Spectroscopic Probes of Star Formation and Black Hole Accretion

To understand galaxy evolution, we need to measure the rate at which stars form and black holes accrete matter as a function of time. The apparently similar shapes of the histories of star formation and black hole accretion with redshift (see Fig. 1), the fact that most AGN also display enhanced star formation, along with the black hole-stellar mass correlation seen in the local Universe (Magorrian et al. 1998; Ferrarese & Merritt 2000), all suggest that the two processes are physically linked.

The mid- to far-IR spectral range includes a suite of atomic and molecular lines and features covering a wide range of excitation, and tracing the physical conditions (excitation, density, ionization, radiation field, metallicity and dust composition) in galaxies (Fig. 2, and Spinoglio & Malkan 1992). Table 1 lists the suite of atomic and ionic fine structure lines which will be covered by the SMI and SAFARI spectrometers onboard SPICA. These lines reveal the detailed physics in the various phases of the interstellar medium (ISM), from HII and photo-dissociation regions (PDR), to the Narrow Line Regions (NLR) excited by AGN. In the highly opaque, dust obscured ISM of actively star-forming galaxies and AGN, the IR lines are among the few probes of the physical conditions in the gas and dust surrounding the supermassive black holes (SMBH) or young, hot stars. The neutral gas surrounding star forming regions can be traced using the temperature sensitive [OIII] lines at 63 m and 145 m, while the ionised gas can be studied using many different tracers to measure temperature, density and abundances. The [NII]122 m to [NII]205 m, [OII]37 m to [OIII]88 m, [SII]18.7 m to [SIII]33.5 m, and [NeII]15.6 m to [NeIII]36.0 m line ratios are individually sensitive to the density (and not to the temperature as the electron temperatures.

Table 1 Fine-structure lines that could be observed by SPICA in the range 0 < z < 4. Solar abundances as log X/H + 12 from Grevesse et al. (2010) and critical densities for collisional de-excitation have been taken from Tielens & Hollenbach (1985); Genzel (1992); Greenhouse et al. (1993).

<table>
<thead>
<tr>
<th>Atom</th>
<th>Solar abundance</th>
<th>Ion/Line</th>
<th>$\lambda$ (m)</th>
<th>I.P. (eV)</th>
<th>$n_{\text{crit}}$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>8.69</td>
<td>[OI] 63.18</td>
<td>–</td>
<td>4.7(5)</td>
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<tr>
<td></td>
<td>[OI] 14.55</td>
<td>–</td>
<td>9.5(4)</td>
<td></td>
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<tr>
<td></td>
<td>[OII] 51.81</td>
<td>35.12</td>
<td>3.6(3)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>[OIII] 88.36</td>
<td>35.12</td>
<td>5.1(2)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>[OIV] 25.89</td>
<td>54.93</td>
<td>1.0(4)</td>
<td></td>
<td></td>
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<td>C</td>
<td>8.55</td>
<td>[CII] 157.7</td>
<td>11.26</td>
<td>2.8(3)</td>
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<tr>
<td>Ne</td>
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<td>[NeII] 12.81</td>
<td>21.56</td>
<td>5.6(5)</td>
<td></td>
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<tr>
<td></td>
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<td>2.9(5)</td>
<td></td>
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<td>[NeIII] 36.01</td>
<td>40.96</td>
<td>4.2(4)</td>
<td></td>
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<td>[NeV] 14.32</td>
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<tr>
<td></td>
<td>[NeVI] 7.65</td>
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<td>N</td>
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<td></td>
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<td>[NIII] 57.32</td>
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<tr>
<td>Mg</td>
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<td>[MgIV] 4.49</td>
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<td>6.3(6)</td>
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<tr>
<td>Si</td>
<td>7.51</td>
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<tr>
<td></td>
<td>[SiVII] 6.49</td>
<td>205.05</td>
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<tr>
<td>Fe</td>
<td>7.50</td>
<td>[FeII] 24.04</td>
<td>–</td>
<td>3.1(6)</td>
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<td>[FeII] 34.71</td>
<td>–</td>
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<td></td>
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<td>7.90</td>
<td>2.2(6)</td>
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<td></td>
<td>[FeII] 35.35</td>
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<td>3.3(6)</td>
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<tr>
<td>S</td>
<td>7.12</td>
<td>[SIII] 18.71</td>
<td>23.34</td>
<td>1.7(4)</td>
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<tr>
<td></td>
<td>[SIII] 33.48</td>
<td>23.34</td>
<td>2.0(3)</td>
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<td></td>
<td>[SIV] 10.51</td>
<td>34.79</td>
<td>5.6(4)</td>
<td></td>
<td></td>
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<tr>
<td>Ar</td>
<td>6.40</td>
<td>[ArII] 6.99</td>
<td>15.76</td>
<td>1.9(5)</td>
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</tr>
<tr>
<td></td>
<td>[ArIII] 8.99</td>
<td>27.63</td>
<td>3.1(5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ArIII] 21.83</td>
<td>27.63</td>
<td>3.5(4)</td>
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are generally higher than the excitation states of the lines above). The strength and hardness of the radiation field can be derived from pairs of the same element in different ionisation states and again the SPICA wavelength range is ideal. Examples are the [NII]122 or 205µm, the [NeII]15.6µm to [NeII]12.8µm and the [OIV]26µm to [OIII]52 or 88µm line ratios. The ratio of the [OIII] to [NII] lines can be used to derive relative abundances of O and N, two key elements in the gas chemistry (see Fernández-Ontiveros et al. 2017). Other strong lines such as [SII]34.8µm or [CII]158µm probe the interface between the neutral and ionised gas. The SFR can be obtained via low-ionization lines (e.g. [NeII]12.8µm, [NeIII]15.5µm, [SII]18.7µm), while the AGN accretion rate can be measured via high-ionization lines (e.g., [OIV]25.9µm, [NeV]14.3µm and 24.3µm). Furthermore, fine-structure lines and measures of small grain dust (PAHs) and the mid-IR thermal dust continuum can be used to disentangle AGN emission from star formation (Genzel et al. 1998; Armus et al. 2006, 2007; Farrah et al. 2007; Spoon et al. 2007; Ho & Keto 2007; Veilleux et al. 2009; Petric et al. 2011; Stierwalt et al. 2014) and AGN (Spinoglio et al. 2005; Lutz et al. 2008; Schweitzer et al. 2008; Tommasin et al. 2008, 2010; Alonso-Herrero et al. 2012; Spinoglio et al. 2015; Fernández-Ontiveros et al. 2016). As an example, we show in Fig. 3 for a sample of local active galaxies, the line ratios of [OIV]25.9µm/[NeII]12.8µm versus [NeV]14.3µm/[NeII]12.8µm, which both measure the strength of the AGN, while the equivalent width of the PAH emission feature at 11.25µm as well as the equivalent width of the [NeII]12.8µm measure the strength of the starburst component in galaxies (Tommasin et al. 2010).

However, where Spitzer and Herschel detected only the brightest galaxies at redshifts z>0.5 (Sturm et al. 2010; Pope et al. 2008; Menéndez-Delmestre et al. 2009; Riechers et al. 2014; Zhao et al. 2016), SPICA will reveal the properties of the bulk of the IR galaxy population up to redshifts of z=3-4 (Spinoglio et al. 2012). The detected lines and dust features will allow us to unambiguously quantify in each galaxy the contribution of star formation and AGN to the bolometric luminosity in each galaxy. In Fig. 4 we illustrate how specific IR line ratios can discriminate among nuclear activity from AGN, normal star formation and also low metalliclicity star formation. We notice that orders of magnitude in the line ratios separate the different objects, making this diagram very powerful, i.e. the analog of the classical optical BPT diagram (Baldwin et al. 1981), but using extinction-free IR lines.

Fig. 5 shows the predicted intensities for the strongest mid- and far-IR lines in two nearby starburst galaxies (M82 and IRAS 17208–0014), and two AGN (NGC 1068 and NGC 4151). For all galaxies, the line intensities have been scaled to a luminosity of L=10^{12} L_☉. The lines of [NeII]12.8µm, [OIII]52, 88µm, [OIV]25.9µm, [NeV]14.3µm, 24.3µm, [NeVI]7.6µm will be detected in less than few hours for the bulk of both starburst galaxies and AGN (L ~ 10^{12} L_☉) at the peak of star formation and SMBH accretion activity (1 < z < 3).

The SAFARI grating spectrometer at low resolution (R~300) will detect [OIV]25.9µm at z=1 in galaxies with L~10^{11} L_☉, at z=2 in galaxies with L~3x10^{11} L_☉, and at z=3 in galaxies with L~10^{12} L_☉ in a few hours. These luminosities correspond to the knee of the luminosity function, L*, or characteristic luminosity (Schechter 1976), at each redshift. Simultaneously, SAFARI will detect many other diagnostic lines of the ionized and neutral ISM, such as the star formation tracers of [NeII]12.8µm, [NeIII]15.5µm, [SII]18.7µm and 33.4µm, and at longer wavelengths the photodissociation region tracers of [O]63µm and 145µm and [CII]158µm. Fig. 4 shows the IR spectrum of the local active galaxy MCG-3-34-64, rescaled to a luminosity of L=10^{12} L_☉ at redshifts z from 1 to 4, illustrating that the SPICA spectrometers will be able to detect both the continuum and the brightest lines in such a galaxy up to z ~ 4 in a few hours.

SPICA will be able to obtain deep 34-230µm low-resolution spectra of ~ 1.000 galaxies, equally spaced in luminosity and redshift bins, up to a redshift of 4.
Figure 3. Left panel: $[^{12}\text{Ne}]/[^{12}\text{Ne}]$ ratio versus the $[^{25}\text{O}]/[^{25}\text{Ne}]$ line ratio. Both axes correlate with the strength of the AGN. The black line shows the behaviour of the analytical model for this diagram (Tommasin et al. 2010). Right panel: $[^{12}\text{Ne}]$ equivalent width versus the PAH 11.25 line equivalent width. The axes in this plot correlates with the strength of the star formation component in each galaxy. The black line shows the behaviour of the analytical model for this diagram (Tommasin et al. 2010).

$z=3.5$ in a total integration time of $\sim 2000$ hrs. Unbiased, deep low-resolution ($R\sim 50-120$) SMI spectrophotometric surveys will be able to cover 10 deg$^2$ in $\sim 600$ hrs. and detect $\sim 30,000$ galaxies.

JWST will not cover the spectrum above $\lambda = 28.8\mu m$, limiting its capability to measuring spectra of galaxies and AGN above $z\sim 2$ in the rest-frame mid-IR. This can be done with JWST with the $[^{12}\text{Ar}]$ and $[^{12}\text{Ne}]$ lines, but these will be a factor of 3–4 fainter than the MIR lines accessible to SPICA. A direct comparison suggests that SPICA will be 25 to 2000 times faster than JWST at diagnosing the power sources in dusty galaxies at $z=2, 3$, respectively.

ALMA cannot trace far-IR cooling lines (e.g., the $[^{12}\text{O}]/88\mu m$) at redshifts lower than $z<3$, and cannot probe the dust and gas spectral features shortwards of $\sim 300\mu m$, leaving for SPICA the unexplored territory which covers the peak of the SFR and BHAR density functions ($1<z<3$), at mid- to far-IR wavelengths.

3.1 Measuring the unobservable primary ionizing spectrum of AGN and starburst galaxies

The intrinsic primary unattenuated ionizing spectrum of AGN or starburst galaxies cannot be observed from the Lyman limit up to several hundred eV, because of galactic and intrinsic absorption. Fortunately, when photons are the dominant ionization source, the shape of the primary ionizing spectrum responsible for any photoionized source can be indirectly inferred from the strength of the IR emission lines. In the nearby Universe, SPICA will detect the full range of mid- to far-IR fine-structure lines, providing a powerful probe of the intrinsic, ionizing spectrum, while at higher redshift, e.g. $z \sim 1-2$, depending on the luminosity of the galaxy, SPICA will still be able to detect the brightest lines of, e.g., $[^{12}\text{Ne}]/12.8\mu m$, $[^{15}\text{Ne}]/15.5\mu m$, $[^{26}\text{O}]/52$ and $88\mu m$, $[^{26}\text{O}]/26\mu m$ and $[^{12}\text{Ne}]/14.3$ and $24.3\mu m$, which are sufficient to sample the spectrum.

Fig. 7 (upper panel) shows how the observed IR emission lines trace the primary spectrum of the Seyfert galaxy NGC4151, which is not observable from 10 to 200eV, where the signature of the BH accretion disk (big blue bump) should become prominent (Malkan & Sargent 1982). This method has been applied to ISO spectra of bright Seyfert galaxies, e.g. NGC4151 and NGC1068 (Alexander et al. 1999, 2000), and Spitzer spectra of local AGN (Meléndez et al. 2011). Fig. 7 (lower panel) shows a similar plot for starburst galaxies, where the stellar spectrum can be traced by the IR lines, free from dust extinction. This often leads to unexpected results. For example, observations of the $[^{26}\text{O}]/26\mu m$ line have revealed that starburst and dwarf galaxies can have, in particular conditions, a significant contribution of ionizing photons with energies above 50 eV (Lutz et al. 1998; Schaerer & Stasińska 1999; Fernández-Ontiveros et al. 2016), which is difficult to reconcile with current stellar population models (Stasińska et al. 2015). Observations of low-redshift starburst and dwarf galaxies with SPICA will have the potential to reveal the physical mechanisms (e.g. strong
3.2 Finding AGN in dwarf galaxies

It has been recently recognised that finding and characterising AGN in dwarf galaxies is a unique way to infer the properties of high-redshift BH seeds (z>5), i.e. accreting BHs with masses of 10^5–10^6 M☉, probably associated with low-metallicity environments (Baldassare et al. 2016a). Furthermore, dwarf galaxies are thought to be the local analogues of the high-redshift galaxies responsible for cosmic reionization, due to escaping photons produced by strong star formation (Ly α emitters; Sharma et al. 2016; Izotov et al. 2016; Schaerer et al. 2016) and/or by AGN activity from accreting BH of 10^5–10^6 M☉ (Madau & Haardt 2015). The IR line ratio diagram shown in Fig. 3, which will be populated with SPICA line observations, is ideal for measuring the AGN contribution in dwarf galaxies; this is because dwarf AGN are elusive in X-ray surveys and many of them are contaminated by strong star formation in classical optical BPT (Baldwin et al. 1981) diagnostics (Baldassare et al. 2016b; Simmonds et al. 2016). The [NeII] and [NeIII] lines will be detected at low redshift with SMI at high spectral resolution and at increasing redshift with SMI at medium resolution and with SAFARI.

4 Synergies with Future Facilities

SPICA will study the physical processes driving galaxy evolution, through sensitive mid- to far-IR observations of deeply embedded regions that characterize galaxy formation and evolution at the peak of the SFR and BHAR (1<z<4). JWST, due to its shorter wavelength range, will cover the same redshift range at shorter rest-frame wavelengths (e.g. at z=3 for λ<7μm and at z=2 for λ<9μm), missing most of the fine-structure diagnostic lines of Table 1 and having a greatly reduced ability to detect most dust enshrouded and obscured galaxies and AGN, due to the increasing extinction at shorter wavelengths. SPICA will be able to survey large areas of the sky, and find new samples of IR-bright, high-redshift galaxies. JWST will be able to study in a greater spatial detail the low-redshift Universe (z<1) and perform cosmological studies of the high-redshift Universe in the UV/optical rest-frame. In the submillimeter, ALMA and the NOrthern Extended Millimeter Array (NOEMA), will map lower excitation emission line processes and colder dust continuum, with respect to

http://www.iram-institute.org/EN/noema-project.php

Figure 4. Line ratio diagram of [NeIII]15.5μm/[NeII]12.8μm vs [OIV]25μm/[OIII]88μm with the comparison of the data of local Universe AGN, LINERs, starburst galaxies, and dwarf galaxies with some models. This diagram is able to disentangle nuclear activity from AGN, normal star formation, as well as low metallicity star formation, in e.g. dwarf galaxies (Fernández-Ontiveros et al. 2016). SPICA will be able to measure these line ratios and separate the power sources in active galaxies to z~4.
Figure 5. Predicted intensities for the mid- and far-IR fine-structure lines covered by SPICA for starburst galaxies (M82 and IRAS 17208–0014; left panel) and AGN (NGC 1068 and NGC 4151; right panel), all scaled to a luminosity of $10^{12} \, L_{\odot}$. Filled circles correspond to tracers of AGN activity, triangles to lines typically dominated by star formation, squares to typical PDR lines, and open circles to transitions of warm molecular gas. The predicted line intensities are compared to the 5,1 hour (dotted lines) and 10 hours (solid lines) sensitivities for SMI/HR (in yellow), SMI/MR (in blue), and SAFARI/LR (in green). Additionally, black-dashed lines indicate the sensitivities for JWST/MIRI-MRS (10 hours, from Glass et al. 2015) and Herschel/PACS (5 hours, 1 hour). In less than few hours, SPICA will be able to detect the main star formation and AGN tracers (e.g. [NeII]12.8 µm and [O IV] 25.9 µm) at the peak of star formation and SMBH accretion activity ($1 < z < 3$), for starburst galaxies and AGN at the knee of the luminosity function.

5 CONCLUSIONS

The SPICA mission, with its 2.5-m actively-cooled telescope and powerful instruments, will make a giant step forward in understanding galaxy formation and evolution, through IR spectroscopy of individual galaxies and deep photometric and spectrophotometric surveys for large statistically significant samples. The IR spectral range hosts a powerful suite of diagnostic tools, able to...
penetrate even the dustiest regions and will enable us to probe galaxy evolution in several unique ways, by:

(i.) Obtaining the first physical determination through IR spectroscopy of the star-formation rate and of the black hole accretion rate histories across cosmic times up to a redshift of $z \sim 4$.

(ii.) Studying AGN accretion and feedback and their impact in the evolution of star formation, through detection and characterisation of far-IR molecular and atomic line profiles.

(iii.) Measuring the rise of metals from the distant Universe to the present day through spectroscopy of IR lines, which minimises the effects of dust extinction and eliminates those of temperature uncertainties and fluctuations in the ionized gas.

(iv.) Studying early AGN and starburst-dominated galaxies in significant samples of dusty galaxies up to a redshift of $z \sim 6$, through deep (spectro)-photometric surveys.

(v.) Detecting and characterizing some of the youngest and most luminous galaxies in the early Universe when it was only half a billion years old.

With a large $\sim 2000$ hrs. spectroscopic survey, SPICA/SAFARI could obtain individual high S/N spectra of over 1000 galaxies to $z \sim 4$. These observations will simultaneously detect diagnostic lines of the ionized and neutral ISM, characterising the local environment and quantifying the contribution from young stars and AGN to the bolometric luminosity. SPICA/SMI will perform similar spectroscopic studies at lower redshifts ($z < 2$) with low-resolution, wide field surveys, to detect and characterize thousands of dusty galaxies via their PAH feature and hot dust emission. No other currently planned telescope will be able to perform this type of detailed spectroscopic and wide-area spectro-photometric investigation. SPICA will fill the large spectral gap left between ALMA (observing above 300µm) and JWST (below 28µm). In this spectral range, SPICA will observe the ionic fine structure lines, the $H_2$ as well as
many other molecular lines (e.g. from H₂O, OH, CO) and PAH features in the rest-frame mid-IR in galaxies at the peak epoch of star formation, as well as those from the molecular gas and PDRs in the far-infrared.

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