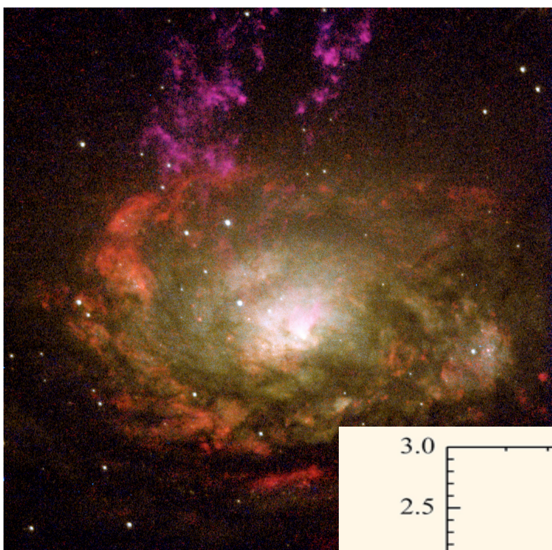
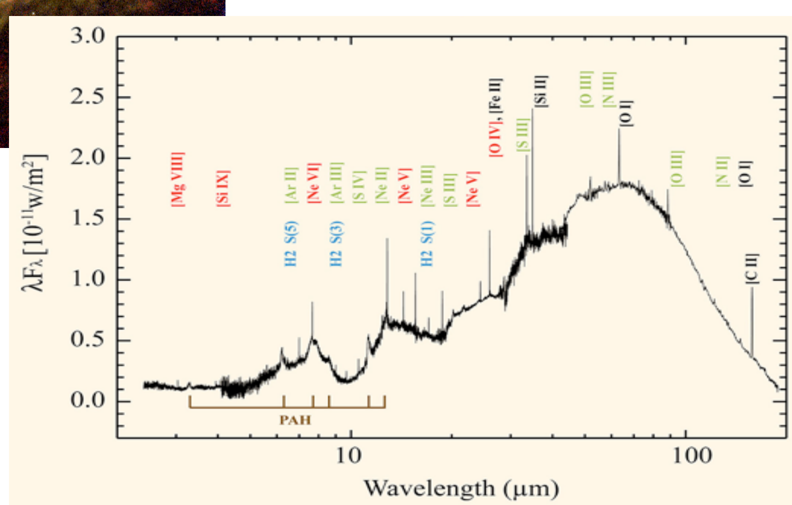
Lifting the Cosmic Veil on the Co-evolution of Black Holes and Galaxies: The Role of Far-Infrared Spectroscopy from Space*

L. Armus (lee@ipac.caltech.edu)
Spitzer Science Center, Caltech
(626-395-8569)

P.N. Appleton (IPAC), A.W. Blain (Caltech), C.M. Bradford (JPL), C.R. Bridge (SSC), R. Chary (SSC), E. Daddi (CEA Saclay), V. Desai (SSC), M. Harwit (Cornell), G. Helou (IPAC), P.F. Hopkins (UC Berkeley), M. Malkan (UCLA), J. Melbourne (Caltech), E.J. Murphy (SSC), P. Ogle (SSC), C. Papovich (Texas A&M), A. Pope (NOAO), D. Riechers (Caltech), J.R. Rigby (OCIW), J.D. Smith (Toledo), G. Stacey (Cornell), H.I. Teplitz (SSC), M.J. Ward (Durham), M. Werner (JPL)





*A whitepaper submitted on 2/15/09 in response to the call from the Astro2010 panel

Key Questions

In order to obtain a comprehensive picture of galaxy evolution, we need to accurately measure the growing population of stars and super-massive black holes in galactic dark matter halos. The processes that regulate this evolution are invariably those that are the most difficult to simulate, namely gas heating and cooling, star formation, black hole fueling, and feedback from both supernovae and Active Galactic Nuclei (AGN).

One of the most striking results to appear in the last decade has been the discovery that the masses of the central black holes and stellar bulges in galaxies are correlated (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhart et al. 2000). The fact that in present-day galaxies the ratio of the mass of the stellar bulge to the central super-massive black hole has a constant value of about 700, implies that star formation and black hole accretion are intimately linked in the evolutionary history of a galaxy. Precisely how this relationship is built up over cosmic time is one of the key questions driving observational and theoretical astrophysics today, as well as providing considerable motivation for the next generation of ground-based and space-based observatories. There are already hints that the tight local correlation was not always in place. The black holes of the most luminous quasars at $4 < z < 6$ appear much more massive than expected based on an extrapolation of the local relation (Riechers et al. 2008), while those of some $z \sim 3$ sub-millimeter galaxies (SMGs) may be smaller than their stellar masses would suggest (Borys et al. 2005; Alexander et al. 2008).

Models that study the growth of galaxies via mergers in the context of cosmological simulations are able to explain the colors, morphologies, and kinematics of elliptical galaxies as well as the luminosity function of QSOs (Springel & Hernquist 2005; Hopkins et al. 2008; Robertson 2006). Mergers provide a natural link between the stellar and black hole mass in galaxies, since they can rapidly funnel large amounts of gas to the nuclei, fueling a powerful starburst and feeding a growing black hole. Cold accretion of halo gas along galactic filaments has also been proposed as a viable mechanism to build up stellar mass and galactic disks at high redshift, and has shown similar success in explaining many of the properties of local galaxies (Keres et al. 2005; Dekel et al. 2009). While gravity drives the formation and evolution of galactic halos, the properties of galaxies we actually observe are critically dependent upon gas cooling, star formation, and energetic feedback from supernovae and AGN.

Despite the success of simulations, a number of critical questions still remain, such as: When do the first heavy elements appear, and how does the chemical history of the Universe set the stage for the collapse of the first stars and the build-up of galaxies? When and how do the first black holes form and how does the black hole – bulge mass relation evolve with redshift? How and when does feedback from stellar winds, supernovae and AGN regulate star formation?

***Cover**: Hubble Space Telescope image and Infrared Space Observatory mid and far-infrared spectrum of the nearby Circinus galaxy. The dusty center shows evidence for a massive black hole, a powerful starburst, and outflows of hot gas.*

Background

Galaxies experiencing powerful bursts of star formation are usually blanketed in a great deal of dust. The dust reprocesses the X-ray and UV photons producing far-infrared (FIR) emission. The most luminous, star-forming galaxies have typically been discovered via their enhanced, FIR emission (Soifer et al. 1984, 1986). These galaxies emit more than 90% of their total energy in the FIR, as dust absorbs and re-radiates most of the energy originally released by young, hot stars. Studies with ISO and Spitzer have shown that Luminous Infrared Galaxies (LIRGs, having infrared luminosities of $10^{11} - 10^{12}$ $L_\odot$) account for ~50% of the co-moving infrared luminosity density at z~1 (Elbaz et al. 2002; Magnelli et al. 2009), with Ultraluminous Infrared Galaxies (ULIRGs – galaxies with infrared luminosities above 10^{12} $L_\odot$) making up an increasing fraction at higher redshifts. More that half of all the light emitted from stars is absorbed by dust and re-emitted in the infrared (Elbaz & Cesarsky 2003).

Models and observations of luminous starbursts and AGN suggest that periods of significant mass accretion onto a central black hole may also preferentially occur during episodes of enhanced nuclear star-formation (Soltan 1982; Yu & Tremaine 2002; Hopkins et al. 2007). At low redshift, ULIRGs may derive up to 40% of their power from buried AGN (Armus et al. 2007; Farrah et al. 2007). Stacking of faint $1 < z < 3$ ULIRGs selected with Spitzer at 24μm also suggests a significant contribution from buried AGN to the total power emitted in the FIR (Papovich et al. 2007, Daddi et al. 2007). Similarly, observations of $z > 6$ QSOs show powerful circum-nuclear starbursts (Walter et al. 2009). The deepest infrared and X-ray surveys are consistent with the idea that the majority of star-formation and black hole growth, over more than 75% of cosmic time, takes place in environments that are obscured by dust and gas.

Although we have broadly measured the evolution of the bolometric luminosity density from $0 < z < 3$, the relative contribution of AGN and star formation at early epochs is quite uncertain. Furthermore at $z > 3$, estimates rely on extrapolations from rest-frame UV observations which suffer from dust attenuation and are demonstrably inaccurate due to the limited sensitivity of current mid and FIR observations. If we are to understand how galaxies and black holes grow, it will be critical to piece together a complete picture of this evolution. This requires the ability to make extremely sensitive measurements of the most obscured regions at the centers of distant, faint galaxies.

Diagnostics of the Dusty Interstellar Medium

In a galaxy with a great deal of circum-nuclear dust, direct measurements of the black hole and the young stars are difficult. However, by measuring the ionization state of the gas along with the dust, it is possible to infer the ambient radiation field and the relative fraction of the bolometric luminosity generated by the starburst or AGN. There are a number of complementary paths traditionally used to uncover buried AGN. Deep radio continuum observations are very efficient at finding the emission from radio-loud AGN at high redshift (Yun et al. 2001). Hard X-ray (> 2 keV) imaging and spectroscopy provides a powerful tool to find and characterize AGN, which is relatively insensitive to large columns of gas and dust along the line of sight ($N_{HI} \leq 10^{24}$ cm^{-2}). FIR spectroscopy provides a direct measure of the basic physical properties (density, temperature, pressure and kinematics) of the ionized ($T \sim 10^4$ K) and neutral atomic gas, the warm ($T \sim 100$-500 K) molecular gas, and the dust in galaxies. It is the only part of the electromagnetic spectrum that gives a complete picture of all phases of the interstellar medium, from atoms to complex molecules.

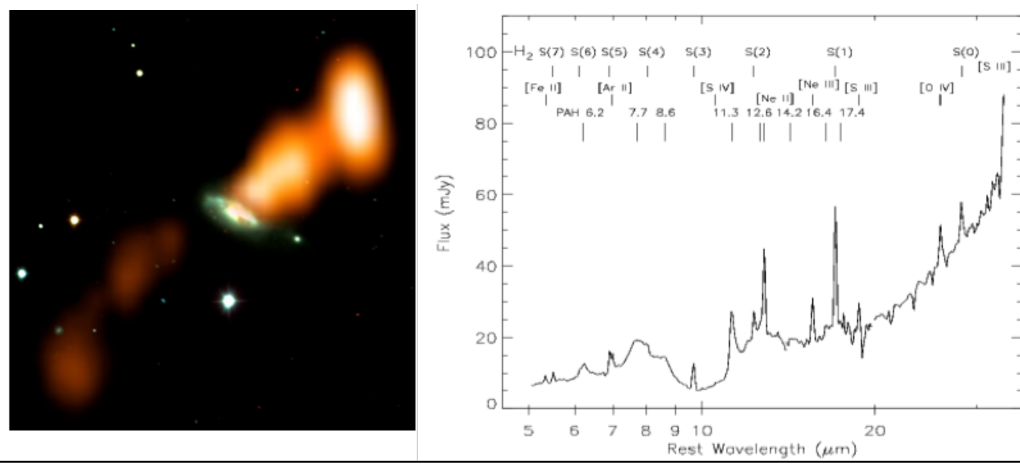


Fig. 1: Visual & radio composite image (left) and Spitzer IRS spectrum (right) of the z=0.045 radio galaxy 3C293. The IRS spectrum shows unusually strong H_2 emission lines from warm molecular gas in the galactic disk heated by the radio jet.

The infrared is rich in atomic, fine-structure emission lines of Oxygen, Carbon, Nitrogen, Neon, Sulfur and Silicon (e.g., [NeII] 12.8μm, [NeV] 14.3μm, [OIV] 25.9μm, [OI] 63μm, [CII] 158μm, and [OIII] 88μm, and [NII] 122μm – see spectrum of the Circinus galaxy on the cover page). The lines cover more than an order of magnitude in ionization potential and they strongly constrain the density and temperature of the ionized and neutral gas, the strength and hardness of the interstellar radiation field, and the relative importance of the black hole vs. the hot young stars to the overall energy budget (Brandl et al. 2006, Armus et al. 2007, Farrah et al. 2007). The mid-infrared lines can also be used to estimate the mass of the black hole (Dasyra et al. 2008), and trace high-velocity gas at the base of a dusty, nuclear outflow (Spoon et al. 2009). Poly-cyclic Aromatic Hydrocarbons (PAHs), whose carriers are stochastically heated by individual photons but easily destroyed in harsh radiation fields, are also excellent probes of the ionizing photon flux. With Spitzer we have classified hundreds of LIRGs and ULIRGs using these mid-infrared diagnostic features. We have also been able to identify PAHs in luminous galaxies out to z ~3 (Yan et al. 2005, Houck et al. 2005; Pope et al. 2008; Menendez-Delmestre et al. 2007; Valiante et al. 2007; Huang et al. 2007; Rigby et al. 2008), providing the first detection of organic molecules in the early Universe.

Observations of the rest-frame, mid-infrared molecular hydrogen (H_2) lines (S(7) 5.51μm through S(0) 28.21μm) and the mid-J CO lines can reveal the temperature, mass, and dynamics of the warm molecular gas heated by young stars and AGN. Warm molecular gas can be an effective indicator of AGN feedback, as has recently been demonstrated by

Spitzer observations of low-redshift radio galaxies (Ogle et al. 2007). In these objects, the H_2 lines dominate the mid-infrared spectrum and can emit up to 10% of the total infrared luminosity. The large H_2 / PAH, and H_2 /X-ray ratios suggest heating of the molecular gas by the radio jet (Fig.1) and an extremely low star-formation efficiency. The mid-J (J=8-15) infrared transitions of CO can also be used to diagnose the warm molecular gas in a starburst or AGN (Bradford et al. 2003, Weiß et al. 2007), providing a critical complement to mm CO observations of the cold gas. In very dense gas, OH, CH, H_2O, and CO are often seen in absorption, providing a direct measure of column densities and abundances of optically thin species (see Fig. 2).

It is believed that the gas which gives rise to the first generation of stars cools through emission lines of H_2 (Santoro & Shull 2006). After the massive first generation stars explode as supernovae, injecting heavy elements into their surroundings, cooling of the gas is dominated by infrared fine-structure lines. Evidence for the importance of the FIR cooling lines exists at low and high redshifts. The [CII] 158µm and [OI] 63µm lines are often the brightest single lines in the spectrum of a star-forming galaxy, each emitting up to 1% of the total FIR luminosity (Malhotra et al. 1997; Luhman et al. 1998) and providing a direct and accurate measure of the star formation rate. In galaxies with the most intense starbursts, the [OI] or [OIII] 88µm line can even surpass [CII] as the primary coolant (Brauher et al. 2008). Recently, the detection of redshifted [CII] in a z=6.24 QSO (Walter et al. 2009) was used to estimate a star-formation rate of 1700 $M_{\odot} yr^{-1}$ in this powerful AGN, providing further evidence for a connection between black hole growth and star formation at the earliest epochs.

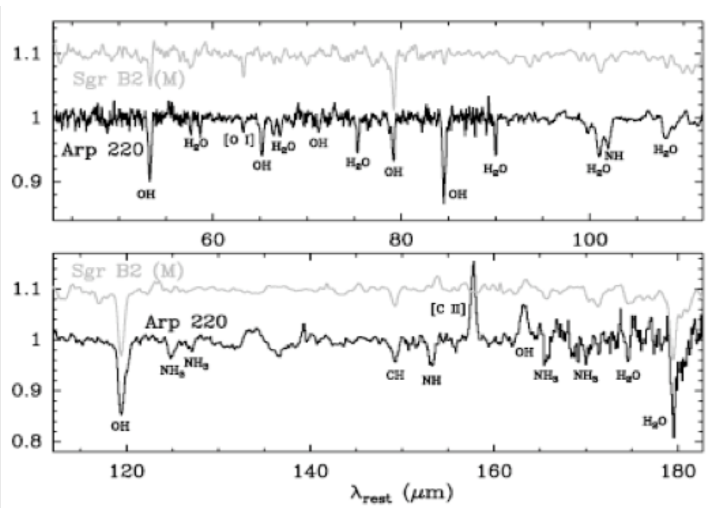


Fig. 2: Comparison of the far-infrared molecular absorption features in the Galactic center molecular cloud complex, Sgr B2, to that from the nearest ULIRG, Arp 220 (Gonzalez-Alfonso et al. 2004). Multiple species are evident, including the striking presence of H_2O in Arp 220 – one of the most extreme star-forming environments in the local Universe.

Since dust absorbs and re-emits the vast majority of the radiation in a starburst, the FIR continuum is dependent on the temperature, composition, and emissivity of the grains. Measurements of the FIR spectrum of high-redshift galaxies can therefore solidly establish the history of early chemical enrichment in the first objects. There is evidence, both among the field galaxy population, and in the spectra of QSOs, for dust having been produced within a few hundred million years after the Big Bang (Maiolino et al. 2008). The physical composition of this dust appears to be quite different from the graphite and silicate grains seen in the local Universe, suggesting pathways other than red giants and

AGB stars for the production of dust in the early Universe. One suggestion is that this early dust is produced in the explosion of extremely massive (~200 $M_{\odot}$) stars.

The Need for Background-Limited FIR Spectroscopy

With the completion of a number of infrared and sub-millimeter telescopes (WISE, Herschel, SOFIA, JWST MIRI, CCAT, ALMA), this decade will see great advances in our understanding of the dusty Universe. However, the ability to perform the high-sensitivity, broadband, FIR spectroscopy necessary to answer the key questions outlined here will be lacking. Herschel observatory will observe the [CII] and [OI] lines from large samples of nearby galaxies, but its ability to measure faint spectral lines from distant galaxies is limited because it is not cryogenically cooled. For example, the [CII] and [OI] cooling lines in LIRGs at z =1, and ULIRGs at z=2-3 should have line fluxes of about 10^{-19} W m^{-2}. The rest-frame mid-infrared fine structure lines ([NeII], [NeV], [OIV], [NeIII]) will have line fluxes that are an order of magnitude fainter. Therefore, the brightest FIR cooling lines, and the most important infrared diagnostic features will be at least two orders of magnitude fainter than the practical limits of Herschel or SOFIA, for all but the most luminous galaxies at z > 1 (see Fig.3).

The James Webb Space Telescope (JWST) will provide our first glimpse of the earliest galaxies. However, most of the mid-infrared diagnostic lines will pass out of the observable range of the JWST spectrographs (λ < 30 μm) by z ~ 2, and even the 6.2 μm PAH feature will be unobservable for z > 3.8. The Wide-Field Infrared Survey Explorer (WISE) will perform an all-sky survey, reaching nearly three orders of magnitude below IRAS, but will have no spectroscopic capability. The Cornell Caltech Atacama Telescope (CCAT), a proposed 25-m ground based sub-millimeter telescope, will enable rapid searches for high-redshift dusty galaxies, finding thousands of sources per hour. The Atacama Large Millimeter Array (ALMA) will be extremely sensitive for spectral-line observations of distant galaxies found with WISE and CCAT. With its milli-arcsecond spatial resolution, it will provide a measure of the size and temperature profile of the FIR emitting regions in high-redshift galaxies. However, both CCAT and ALMA, being ground-based observatories, will operate only in limited atmospheric windows, rendering large redshift slices, critical for understanding galaxy evolution, inaccessible.

To be able to measure the rest-frame FIR cooling lines in the galaxies which dominate the infrared background at z ~1, and also measure the full suite of rest-frame mid-infrared atomic and molecular gas and dust features in high redshift (z > 2-3) ULIRGs, a broadband, FIR spectrometer, capable of reaching the natural astrophysical background over the ~30-300μm range is required. This instrument would allow us to produce a complete census of AGN and chart the growth of super-massive black holes and stellar mass in dusty galaxies across a significant fraction of the age of the Universe. The required sensitivity and wavelength coverage is impossible to reach from the ground, but could be achieved with a large, cooled telescope in space.

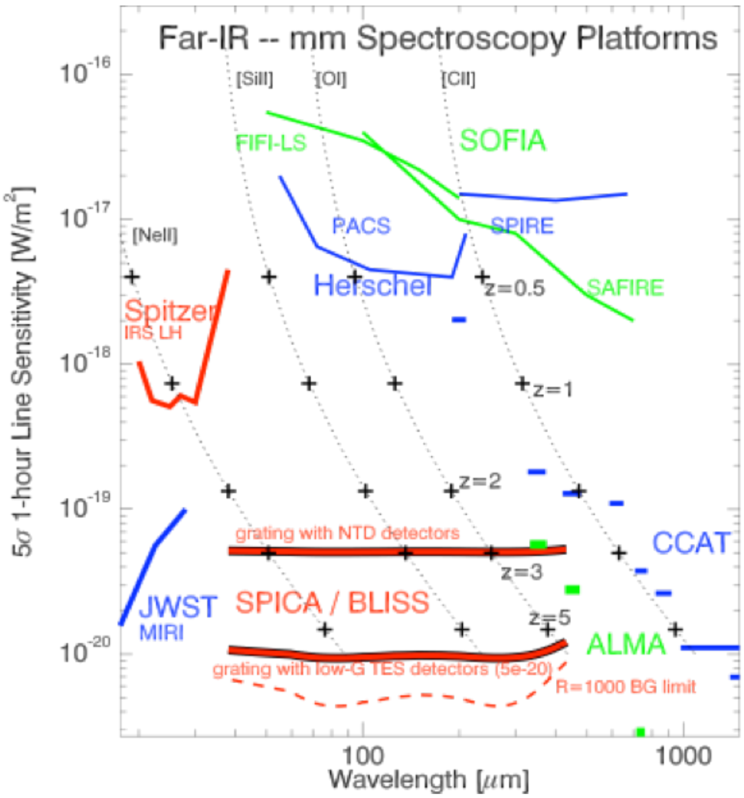


Fig. 3: Anticipated performance of the Background Limited Infrared Sub-millimeter Spectrometer (BLISS) on the Japanese-led SPICA mission, compared to other existing or anticipated far-IR/sub-mm platforms. SPICA/BLISS would have continuous coverage from 38-433 μm, and be about three orders of magnitude more sensitive than Herschel or SOFIA. BLISS sensitivities are calculated assuming 75% aperture efficiency, 25% instrument transmission in a single polarization, and R=700. Also shown are the expected fluxes for a few key infrared emission lines from a ULIRG at $0.5 < z < 5$ illustrating how BLISS will enable measurement of these key features at the earliest epochs.

In our recently released 2008 community plan for far-infrared/sub-millimeter astronomy from space (http://www.ipac.caltech.edu/DecadalSurvey/farir.html), we argue that US participation in the Japanese-led Space Infrared telescope for Cosmology and Astrophysics (SPICA) mission is a high priority for the next decade. SPICA is a 3.5m cryogenically cooled, FIR telescope planned for a 2016/2017 launch, which provides an important and necessary technological and scientific step toward a large (6-10m) US-led single aperture FIR telescope, or a space-based interferometer in the following decade.

Summary

Understanding galaxy evolution and in particular, how the correlation between central super-massive black hole and stellar mass is built up over cosmic time, will drive observation and theory in the next decade. A detailed characterization of the interstellar medium in young, star-forming galaxies, and a full understanding of the role of feedback in regulating star-formation requires an observatory that covers far-infrared wavelengths. A broadband, background limited, FIR spectrometer on a space-based large aperture, cryogenically cooled telescope would enable an impressive scientific synergy with JWST and ALMA, providing a complete census of the dust-enshrouded build up of stellar and black hole mass over the past 10 Gyr. By measuring the ionization state of the atomic gas, the warm molecular gas, and the dust, it will be possible to estimate the true fraction of the IR light contributed by accreting black holes and starbursts, map out the history of chemical enrichment from the earliest galaxies to today, and trace the feedback from AGN and supernovae on the molecular gas that regulates the growth of galactic mass and structure.

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