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OBSERVATIONS OF INTERSTELLAR MATTER IN GALAXIES WITH THE INFRARED SPECTROGRAPH ON SPITZER

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Abstract. The Infrared Spectrograph (IRS) on board the Spitzer Space Telescope, with its superb sensitivity, has opened a new era in performing low and high resolution spectroscopy over the 5–38μm range. The physics of extragalactic targets with mid-infrared flux densities of just a few tens of mJy can now be probed in a matter of minutes and spectroscopy to sub-mJy levels is for the first time attainable. In this paper we present a few of the early extragalactic results of IRS.

1 Introduction

The infrared spectrograph (IRS; Houck et al. 2004a) is one of the three instruments on board the Spitzer Space Telescope (Werner et al. 2004a), the fourth of NASA's great observatories, launched on August 25th, 2003. Routine science operations commenced in December 2003 and the telescope along with all instruments have been performing extremely well. IRS contains four separate modules known by their wavelength coverage and resolution as Short-Low (SL, 5.2–14.5μm), Short-High (SH, 9.9–19.6μm), Long-Low (LL, 14.0–38.0μm), and Long-High (LH, 18.7–37.2μm). The spectral resolution of the SL and LL varies between 64 and 128, while in SH and LH it is fixed to $\sim$600. The slit widths are fairly narrow, and they are set to $\lambda_{\rm max}/85\,$cm, where $\lambda_{\rm max}$ is the longest wavelength for the module. Two Si:As detectors, 128$\times$128 pixels in size, collect the light in the SL and SH modules, while two Si:Sb detectors of the same number of pixels are used in the LL and LH modules. In addition to its spectrographs, IRS contains two peak-up imaging fields which are built into the Short-Low module and have bandpasses centered at 16$\,\mu$m ("blue") and 22$\,\mu$m ("red")[3].

A number of science results based on the first two months of Spitzer's mission were presented in a special issue of the Astrophysical Journal Supplements (vol. 154, 1 Sept. 2004). In this paper we summarize a few of the early extragalactic discoveries made with the IRS, which serve to highlight the vast discovery potential for mid-infrared spectroscopy with Spitzer.

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[3]Details on the IRS instrument design, in flight performance, and sensitivity can be found in Chapter 7 of the Spitzer Observer's Manual, see http://ssc.spitzer.caltech.edu/documents/SOM/

2 New PAH emission features

The pioneering work of the CAM-CVF and SWS spectrographs of the Infrared Space Observatory (ISO) enable us to perform a detail analysis of the mid-IR spectrum. In the process, the ubiquitous nature of emission from Polycyclic Aromatic Hydrocarbons (PAHs) was proven a powerful tool in probing the chemical composition and interstellar radiation field in dust enshrouded regions (see Peeters et al. 2004). It was also shown that PAHs can be used as tracers of the star formation activity in normal and starburst galaxies (see Förster Schreiber et al. 2004).

The improvements by nearly a factor of 100 in sensitivity made it feasible for Spitzer and IRS to discover a number of new PAH emission features. Werner et al. 2004b, discuss in detail new PAH identifications at 6.7, 10.1, 15.8, 17.4, and 19.0μm based on observations of the reflection nebula NGC 7023. A study of the nearby spiral galaxy NGC 7331 (Smith et al. 2004) though, also revealed a broad complex of PAHs at $\sim$17μm (see Fig.1a). The complex, which is almost half as strong as the 11.3μm feature, can be decomposed to the 16.4μm PAH, which had been detected in a handful of Galactic regions by ISO, and to a new much stronger feature at 17.1mum. As result this complex may potentially be an important contributor to the mid-IR luminosity of galaxies. The 16.4μm feature has also been observed in UGC5101 the first such detection in an ultraluminous infrared galaxy (ULIRG) (Armus et al. 2004).

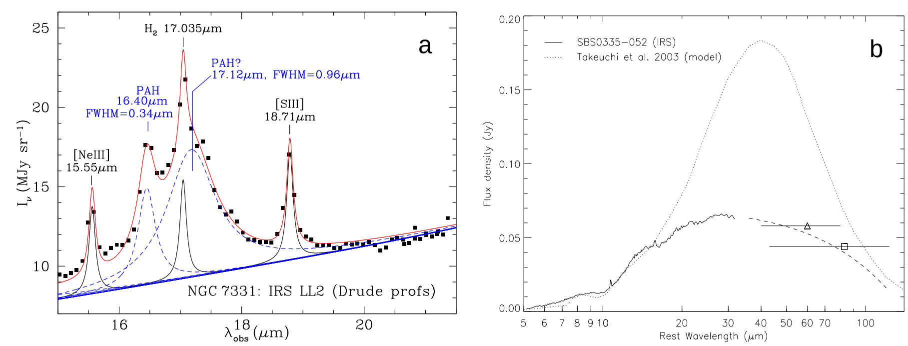

Fig. 1. a) The new 17.1μm feature observed in NGC 7331 by Smith et al. (2004). b) The mid-IR spectrum of SBS 0335-052. Notice that unlike the theoretical predictions and spectra of other star forming galaxies its spectral energy distribution peaks at $\sim$30μm. (see Houck et al. 2004b for more details.)

3 Blue Compact Dwarf galaxies

Low-metallicity Blue Compact Dwarf galaxies (BCDs) have been the focus of a great deal of study at many wavelengths, since these galaxies may represent low-redshift analogs of the first generation of star formation in the early Universe. Several samples of BCDs have been identified from their blue colors and their very low metallicities have been determined using optical recombination lines. However, due to their small size and low IR luminosities, presumably a consequence of the absence of dust because of their young age, infrared spectra of only four of them had been obtained to date.

IRS recently obtained a deep 5–35μm spectrum of SBS0335-052, a BCD galaxy with the 2nd lowest metal abundance observed (Z$\sim$Z$_\odot$/42) (see Fig.1b and Houck et al. 2004b). As it was already known by ISO, despite the burst of star formation in the galaxy and the likely presence of photodissociation regions, the PAH emission features were absent from its spectrum. Strong upper limits were placed on the PAHs and the [SIV]10.51μm and [NeIII]15.55μm lines were clearly detected. Interestingly no [NeII]12.81μm was detected in the spectrum, suggesting a very hard radiation field in the galaxy, probably due to absence of metals, the principle coolant of the gas in the ISM. More surprisingly though, despite the high extinction measured towards the galaxy ($A_{9.7\mu m} \geq$0.4mag) its spectral energy distribution is dominated by a warm dust component peaking at $\sim$ 28μm. The total amount of cold dust in the system is estimated to be approximately 6,000 M$_\odot$. IZw18, the most metal poor galaxy (Z$\sim$Z$_\odot$/50) was also observed by IRS but it was 10 times fainter than SBS0335-052 with a 22μm flux density of $\sim$5mJy.

4 Absorption and emission features in ULIRGs

The extended wavelength coverage of IRS to 38μm greatly facilitates the accurate measurement of the continuum in highly enshrouded sources, such as ULIRGs, as well as the identifications of the absorption features and measurents of the physical properties of the material responsible for these features.

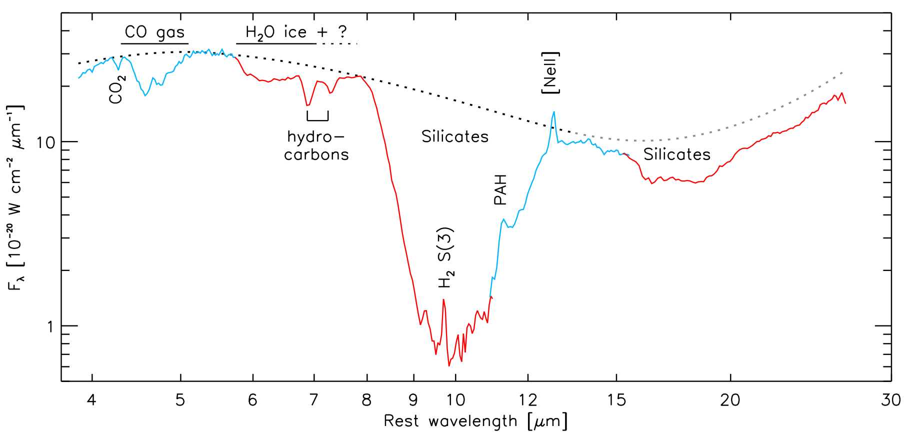

Fig. 2. The IRS spectrum of IRASF00183-7111, a ULIRG at z=0.327, from Spoon et al. (2004). Note the presence of the strong silicate absorption bands, as well as the CO_2, CO, $H_2$0 and HAC features in the 4.0–7.5μm range.

The spectrum of IRASF00183-7111 (see Spoon et al. 2004), obtained with IRS in 15min, demonstrates the quality of the data for a source which was bellow the IRAS 12μm detection limit. The galaxy is strongly obscured ($A_{9.6\mu m} \geq$5.4; $A_V \geq$90) and the central source must be behind a column density of $N_H \sim 10^{23.5}$ cm^{-2}. Based on the mid-IR spectrum the authors estimate that the observed star formation can not account for more than 30% of the IR luminosity of the galaxy and that the central energy source is likely an AGN.

The IRS spectra of three ULIRGs analyzed by Armus et al. (2004), revealed a wealth of emission and absorption features including the first detection of the [NeV]14.32μm line in UGC5101, a direct evidence for a buried AGN, as well as the detection of PAHs in Mrk1014, an infrared luminous QSO.

5 Warm H_2 gas

Molecular hydrogen gas is one of the fundamental constituents of the interstellar medium. Its direct detection though in external galaxies via the typically weak mid-IR rotational lines H_2(0-0), S(0)28.21μm, S(1)17.03μm, S(2)12.27μm, and S(3)9.66μm was challenging. Early IRS results indicate that these lines are routinely detected in normal (Smith et al. 2004) as well as starburst galaxies and AGN (Armus et al. 2004, Spoon et al. 2004). The determination of the warm H_2 gas mass is sensitive to the excitation temperature of the lines and the assumed ortho-para ratio. However, the fact that this method is independent of the metallicity, a major source of uncertainties in estimating cold H_2 gas using the CO emission, should help us in the accounting of the mass distribution in galaxies.

6 Imaging at 16μm: Bridging the gap between ISO and Spitzer

The peak-up cameras of IRS not only enable the acquisition and accurate placement of a science target on the IRS slits, but they can also be used to obtain efficient deep imaging at 16μm and 22μm. The 16μm imaging is particularly interesting since it can provide an anchor point between future Spitzer data and the 15μm measurements performed by most of the ISO deep extragalactic surveys. The power of the cameras has already been demonstrated by the first 16μm detection a Lyman break galaxy at z=2.79 by Teplitz et al. 2004, as well as the imaging of J1148+5251, a Sloan Sky Survey quasar, which at z=6.42 is the most distant object observed with Spitzer to date (Charmandaris et al. 2004).

7 Conclusions

IRS and Spitzer have introduced us to new era in mid-IR spectroscopy of extragalactic sources. If the first few months of the mission is a guide of what lays ahead, new exciting discoveries are just over the horizon.

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