FIFI LS getting ready to fly aboard SOFIA

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ABSTRACT

FIFI LS is the German far-infrared integral field spectrometer for the SOFIA airborne observatory. The instrument consists of two independent integral field spectrometers for two different wavelength bands (45-110 μm and 100-200 μm). A dichroic filter enables simultaneous observation of two different spectral lines in the same field-of view. This allows very efficient mapping of extended regions with *FIFI LS* in many important far-infrared cooling lines with line ratios sensitive to temperature and density.

FIFI LS will become a facility instrument for SOFIA. In the next two years it will become a fully commissioned facility instrument. After its commission, *FIFI LS* will be available for general observing with a large science potential. In this paper, we will also discuss the science of *FIFI LS*.

Keywords: Airborne Instrumentation, Far-Infrared, Integral Field Spectroscopy, SOFIA, FIFI LS

1. INTRODUCTION

NASA together with the German DLR has achieved first light with their unique airborne observatory SOFIA (Stratospheric Observatory For Infrared Astronomy) on May 25 this year.[1] SOFIA is a B747-SP with a 2.5 m telescope built-in.[2] In the next years, SOFIA will make the full infrared wavelength range routinely accessible for more than a decade at unprecedented resolution by carrying its telescope upto 45,000 feet leaving the blocking water vapor behind.

FIFI LS is being developed at the Max Planck Institute for extraterrestrial Physics (MPE) as one of eight first generation instruments for SOFIA. *FIFI LS* will offer simultaneous spectroscopy of two spectral lines, one in each of its two nearly independent spectrometers with a wavelength coverage of 42 to 110 μm and 110 to 210 μm, respectively, at moderate spectral resolution, 50 – 250 km/s. Our instrument will allow efficient mapping of these lines employing integral field spectroscopy. Using a grating spectrometer and an image slicer, a spectrum with an instantaneous wavelength coverage of a few 1000 km/s is obtained for every pixel in a square field of view. This results in a dramatic increase in observing efficiency especially when mapping lines over an extended area compared to a scanning Fabry-Perot or a long-slit spectrometer. Furthermore, the simultaneous acquisition of the spatial and spectral information ensures homogeneity of the observed data and yields redundancy in the data useful for reliable data reduction and removal of instrumental effects. In this paper, we are shortly covering the design and status of development of *FIFI LS*, as well as science cases. The main strength of the instrument is its capability to efficiently map larger areas and provide spectral information of the whole mapped area. The spectral resolution is fully adequate for extra-galactic research and allows an instantaneous coverage of the rotation curve of a galaxy.

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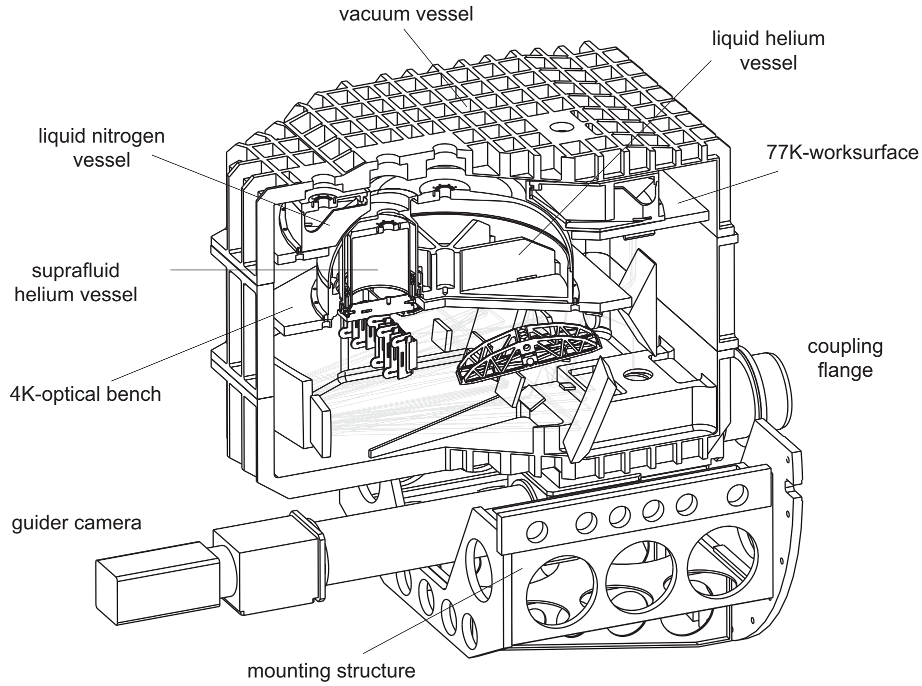

Figure 1. A cut through the *FIFI LS* cryostat. The optical components are mounted on the work surfaces attached to the cryogen vessels. Light from the SOFIA telescope is entering the instrument from the right via the coupling flange.

2. THE INSTRUMENT

In this section, we want to give a short overview over the design of *FIFI LS* and how it works. The instrument is directly attached to the nasmyth tube of the SOFIA telescope. The light from the telescope comes through the nasmyth tube and enters the *FIFI LS* cryostat through the boresight box behind the coupling flange. A dichroic mirror in the boresight box reflects the far-infrared beam into the cryostat while transmitting the visible light to a CCD camera used for guiding. Figure 1 shows a longitudinal section of the *FIFI LS* instrument including optical components. The functional sub-groups of the instrument are:

- Vacuum vessel
- Boresight box and guider camera
- Mounting structure
- Liquid nitrogen vessel
- Liquid helium vessel
- Superfluid helium vessel

The spectrometers and other optical components are mounted to the 4 K- and 77 K-work surfaces (optical benches). The detector is mounted to the work surface of the vessel for the superfluid helium. In the following subsection, the cryostat, the optics, and the detectors are described.

2.1 Cryostat

The main part of *FIFI LS* is the vacuum vessel roughly $1\,m \times 1\,m \times 1\,m$ in size. It contains the three cryogen containers, the optics and the two detector arrays. The main function of the vacuum vessel is to provide the vacuum needed to thermally insulate the cryogenic surfaces. Since all mechanical components are mounted on the vacuum vessel structure, it also forms

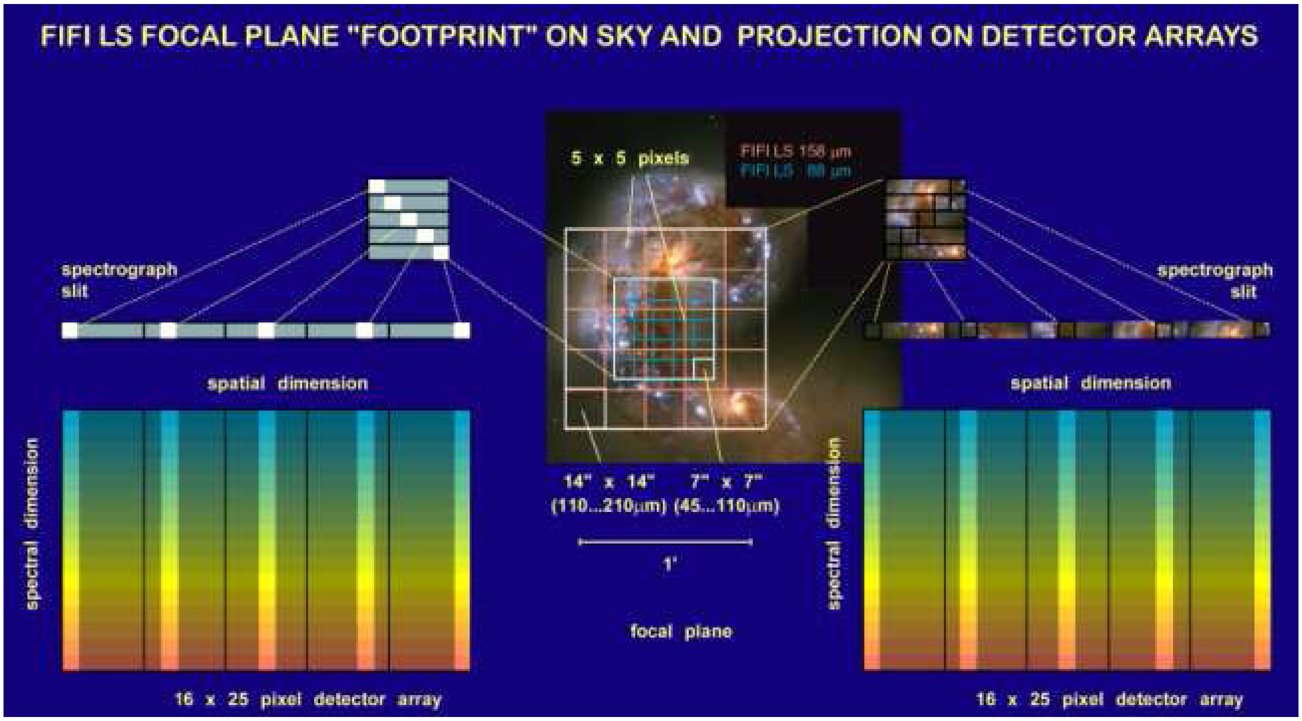

Figure 2. Field-of-view and image slicer concept: The field-of-view, which can e.g. contain the antennae galaxy, consist of 5x5 spatial pixels for each spectral channel Both channels observe the same area, but at different pixel scales. The image slicer dissects the FOV into 5 slices which get rearranged along the slit of the spectrometer to then get dispersed onto 16 pixels. The result is a 25 spectra each 16 pixels wide or a $5 \times 5 \times 16$ data cube.

the primary mechanical structure of the instrument. A CCD-camera under the cryostat is used for guiding and focusing the instrument. To feed the CCD-camera with visible light, an adjustable dichroic beam splitter is used to separate the telescope light into two beams around the cut-off wavelength of $\sim 2\,\mu$m. The visible and near infrared light passes through the beam splitter and reaches the CCD camera. The mid- and far-infrared components of the incoming light are reflected into the cryostat.

The cryogenic system of *FIFI LS* consists of three cryogen vessels that provide the temperature levels required in the instrument. A 31.5 l liquid nitrogen container at 77 K provides cooling for the liquid nitrogen work surface, the entrance optics (a rotating K-mirror and re-imaging optics). The 35 l liquid helium vessel (4.2 K) provides cooling for the liquid helium working surface, the entire spectrometer optics not including the detectors (for optical layout see Sect. 2.2). Since the detector arrays (see Sect. 2.3) require operating temperatures below 4 K, they are mounted onto an additional 3.12 l superfluid helium vessel (a pumped reservoir for superliquid helium at ~ 1.9 K).

2.2 Integral Field Spectroscopy

FIFI LS is a two channel spectrometer that allows simultaneous observations in the wavelength bands 42 – 110 μm and 110 – 210 μm. An interchangeable dichroic mirror splits the far-infrared beam reflecting the shorter wavelength to the “blue” spectrometer and transmitting the longer wavelengths to the “red” one. An image slicer system in each band re-arranges the two dimensional 5×5 pixel field-of-view along a 25 (+4)$\times$1 pseudo-slit which can be easily fed into a grating spectrometer. There is a one pixel wide gap between the 5 individual slices eliminating cross-talk between spatial pixels that are not adjacent in the original field of view. (Though, the sketch in Fig.2 does not show these four gaps between each 5 pixel strip.) The grating spectrometers disperse then the incoming light and achieve a resolution of $R = 1000$ to 3000 depending on wavelength. A large format 25×16 pixel detector array in each spectrometer receives then the spectrum from each of the 25 pixels on a column of 16 pixels.[3,4] More details on the optical design of *FIFI LS* can be found elsewhere.[5,6]

2.3 Detector Arrays

FIFI LS uses two detector arrays, one for each of the two spectrometers. Germanium Gallium-doped photoconductors are used which are sensitive between 40 and 120 μm, and, with the application of about 600 N mm^{-2} of stress, their wavelength sensitivity shifts to 100 - 220 μm.[7,8] An unstressed and a stressed detector array are used in *FIFI LS* for the short and long wavelength spectrometer, respectively.[3] Both arrays have 16×25 pixels putting them among the largest of their kind. The detector array consists of 25 modules each corresponding to one of the 5×5 pixel field-of-view. Each module holds a stack of 16 pixels which allows to apply the same stress to each of the 16 pixels ensuring a uniform response of the pixels.

The detectors are read out with an active Cold Read-out Electronic circuit (CRE)[9] located immediately behind each detector module. The CRE is a specially designed CMOS circuit developed for the Herschel-PACS[10] instrument by IMEC, Leuven/Belgium and can be operated at temperatures of below 4 K.

3. STATUS

In our last SPIE report,[11] we reported on the performance tests of the long wavelength spectrometer. Over the last two years, the short wavelength spectrometer was integrated and the electronics have been updated to its flight version. Currently, last electronics tests are conducted and the short wavelength spectrometer's alignment is checked. The performance testing of the short wavelength spectrometer will happen very soon. Unlike other SOFIA instruments, *FIFI LS* cannot be tested on astronomical sources as the atmosphere is completely opaque at its wavelengths. No ground-based observations of astronomical sources are possible with *FIFI LS*. The performance tests will be again done with the calibration source described in out last SPIE paper[11] which allows the observation of a movable point source and spectral lines. In the upcoming tests, the spectral and spatial resolution of the short wavelength spectrometer will be measured and compared to its design values. The long wavelength spectrometer will be re-tested to ensure that everything is still working. With these tests the transition from instrument development to an working SOFIA facility instrument will begin.

4. FIFI LS BECOMES A FACILITY INSTRUMENT

Almost from the beginning, *FIFI LS* was meant to become available to general observers to some extent while the instrument was owned and operated by the MPE and UC Berkeley.[12] Recently, the *FIFI LS*-team has decided to offer the instrument to SOFIA to make it a full facility instrument. The above mentioned test marks the end of the instrument development at the MPE. The University of Stuttgart will take over to prepare the experiment for the first flights with SOFIA. While the instrument development is complete, there are two main areas where work is still needed before *FIFI LS* can fly on SOFIA. That is the preparation of various reviews before the experiment can fly on board SOFIA and secondly, there is the completion and tests of the periphery and aircraft interfaces of the instrument.

These preparations lead up to the important airworthiness approval. At the same time the pre-shipment review will be conducted. After a successful pre-shipment review, *FIFI LS* can leave Germany and can be shipped to DAOF/Palmdale. *FIFI LS* will be tested and reviewed again to ensure that the experiment survived the shipment. After a successful pre-install review, *FIFI LS* will be tested mounted to SOFIA during line-ops. On-sky observations will only be possible with the optical guider camera as the far-infrared instrument will not be able to see anything. Then the first light and commissioning flights can begin.

With the data from the fist light flights and the commissioning flight in hand, *FIFI LS* can undergo the acceptance review as a SOFIA facility instrument. When the acceptance review is successful, *FIFI LS* is a SOFIA facility instrument and will be open for general observers through the open SOFIA proposal calls.

5. SCIENCE WITH *FIFI LS*

A wide range of research topics can be addressed with *FIFI LS*. The far infrared (FIR) is the wavelength range where the interstellar medium (ISM) can be studied best as it is transparent at these wavelengths and emits strongly in this regime. About all astrophysical research involving the ISM could potentially gain from *FIFI LS* observations. The areas where we expect *FIFI LS* to contribute most include

1. detailed morphological studies of the heating and cooling of nearby galaxies,
2. star formation and the interstellar matter under low metalicity conditions as found in dwarf galaxies,

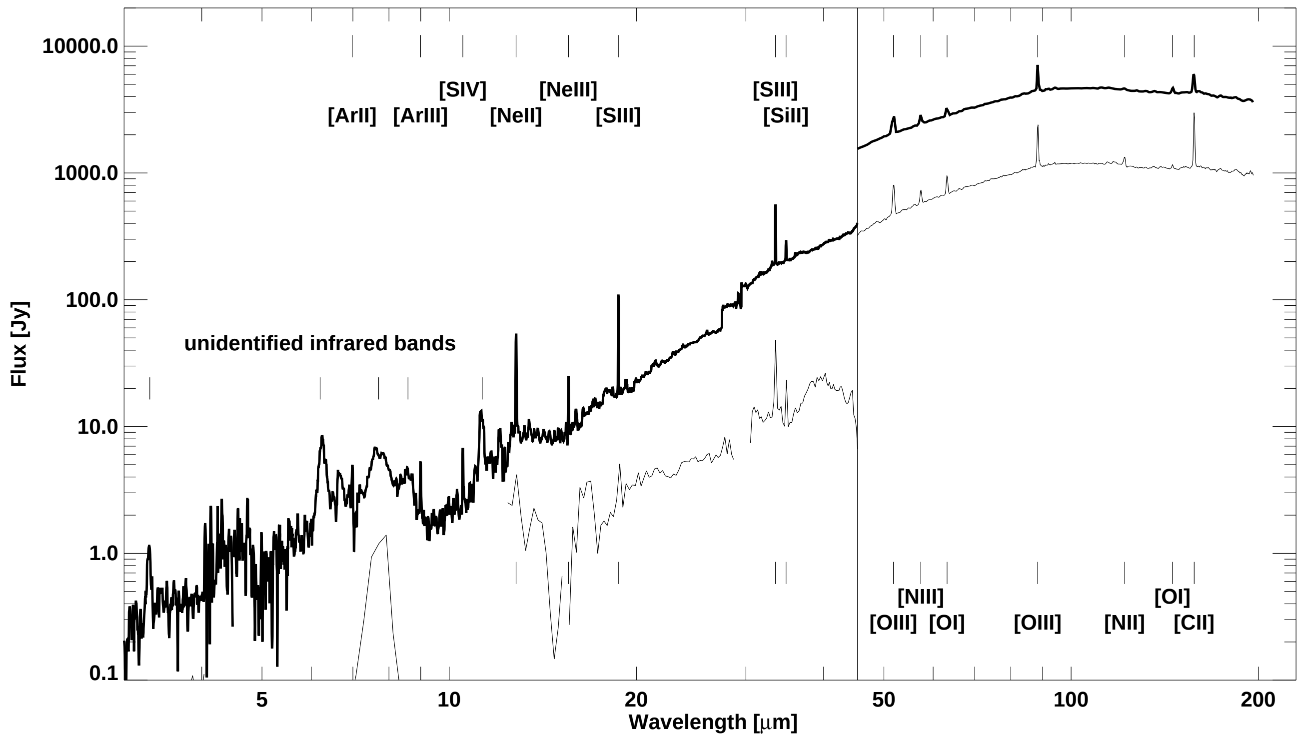

Figure 3. Full far infrared spectrum of M17-N obtained by ISO.[14]

3. active galactic nuclei and their environment,
4. merging and interacting galaxies, and
5. photon dominated regions in galactic high-mass star-forming regions.

The next section elaborates more on star formation and how *FIFI LS* observations of the ISM at different scales help to understand the galactic matter cycle. An extensive account on the science with *FIFI LS* and SOFIA with its other instrument can be found here.[13]

5.1 Star Formation on all Scales

Observations with *FIFI LS* in the far-infrared, which is largely unaffected by dust extinction, will allow us to explore especially star formation taking place in highly obscured regions. The field-of-view (FOV) of *FIFI LS* fits perfectly nearby galaxies. Triggered star formation and the interstellar medium in merging/interacting galaxies (Fig. 2) can be inspected closely as well as the relationship between active galactic nuclei and starburst galaxies. The far infrared offers many diagnostic fine structure lines allowing multi-species investigation of the interstellar medium and star forming regions both locally and in extragalactic sources. All this allows the investigation of star formation in nearby galaxies and their interstellar medium in various environments such as low-metalicity dwarf galaxies or galactic molecular clouds.

The fine-structure lines in *FIFI LS*' wavelength range arise from collisionally excited levels within the ground state of the atoms/ions. These lines are not only important cooling-lines, but especially line pairs allow direct density and temperature measurements, and abundance and excitation estimates. Several species emit in two lines of their triplet ground state. Measuring the line ratio of such a line pair emitted from one and the same species takes out systematic uncertainties due to e.g. uncertainties in the abundances. Depending on the species, the line ratio can depend almost only on temperature or density which makes *FIFI LS* a thermometer and density gauge for the interstellar medium, as *FIFI LS* gives access to all the diagnostic FIR fine-structure lines. As an example, the mid and FIR spectrum of the molecular cloud core M17-N with all its fine-structure lines is shown in Fig. 3.[14] Fig. 4 shows the Horsehead Nebula and illustrates that SOFIA and *FIFI LS* offer a spatial resolution sufficient to study the detailed morphology of e.g. the photon-dominated region (PDR) in the

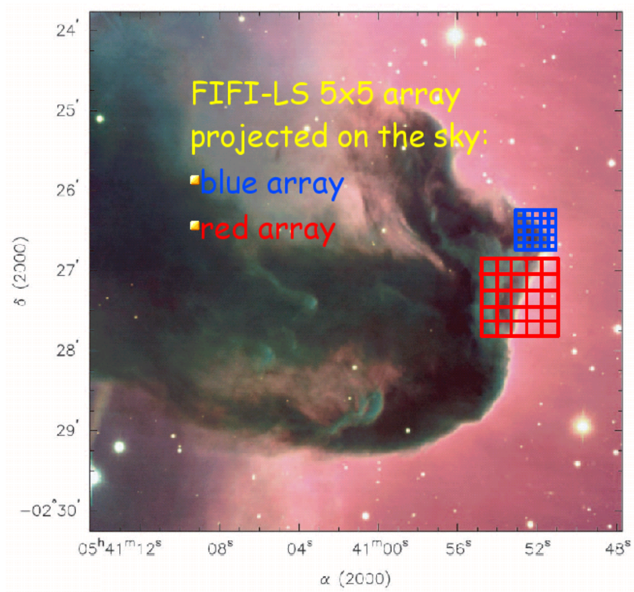

Figure 4. The Horsehead Nebula with the projection of the *FIFI LS* arrays

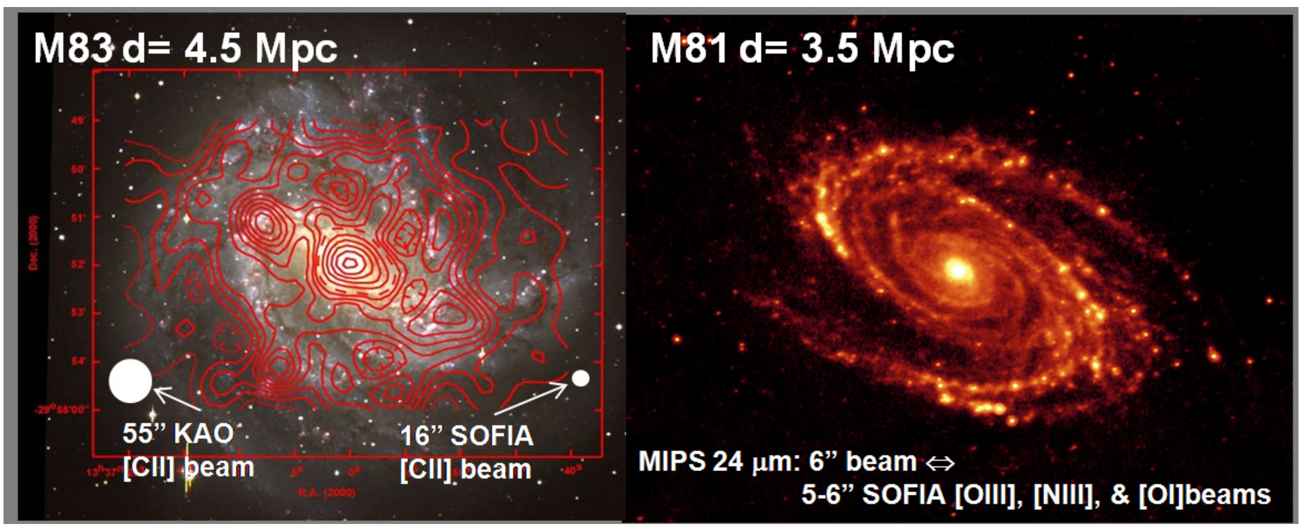

Figure 5. left panel: KAO [CII] map of M83 (d=4.5 Mpc) (contours, 55 beam) superposed on an optical image.[16] right panel: MIPS 24 μm continuum image of M81 (d=3.5 Mpc) with a 6$''$ beam, also the pixel size of *FIFI LS* in the short wavelength spectrometer. *FIFI LS* can achive this resolution on nearby galaxies in the [OIII] 52 μm, [NIII] 57 μm, and [OI] 63 μm lines.[13]

Horsehead Nebula. In a few hours, this PDR can be mapped in several lines. To obtain information on individual velocity components, observations with higher spectral resolution of one of the lines would be needed for example with SOFIA's heterodyne receiver GREAT.[15]

The same important diagnostic transitions can also be observed in nearby galaxies. They reveal details in the large scale physical properties of the ISM in these galaxies. The range of elements and ionization levels also allows estimates of the elemental abundances in the ISM. Furthermore, the FIR fine structure lines provide information on the ambient farUV radiation field, reflecting both the strength, and the effective temperature (hardness) of these fields. Since the UV radiation is generated by hot young stars and the accretion disk surrounding active galactic nuclei (AGN), mapping these lines with *FIFI LS* yields spatially resolved information on the stellar population in the galaxy (e.g., the parameters of the Initial Mass Function), and the contribution from accretion onto a black hole to the general radiation field. Fig. 5 shows M81 and M83, one in the resolution we can expect with *FIFI LS* but imaged by Spitzer in the mid IR and the other in the dominant cooling line [CII] line at 158 μm obtained with the Kuiper Airborne Observatory. This [CII] map was acquired with *FIFI LS*' predecessor FIFI, an imaging Fabry-Perot spectrometer.

Nearby dwarf galaxies further serve as low-metallicity laboratories to explore star formation in the early universe as dwarf galaxies could have model character for lower metallicity environments in the early universe. Observations with *FIFI LS* will allow to analyze star formation in environments with a wide range of metalicities using the major FIR lines.

6. SUMMARY

FIFI LS will become SOFIA's facility instrument for imaging FIR spectroscopy. With its large format photo-conductor arrays and integral-field grating spectrometer, it can map efficiently spectral lines in the FIR. The integral-field spectroscopy is achieved with an image slicer which feeds the 5×5 spatial pixels to the grating spectrometer. The spectral resolution R that can be achieved ranges from 1000 to 3000 depending on wavelength. The mapping capabilities, the spectral resolution, and instantaneous wavelength coverage make *FIFI LS* an ideal instrument to study the ISM on all scales.

The development is almost finished at the MPE and within this year the instrument will be moved to the University of Stuttgart where it is characterized and prepared for first flights and commissioning as a SOFIA facility instrument in 2012. After its commissioning, *FIFI LS* will be available to the community through the open proposal calls from SOFIA.

ACKNOWLEDGMENTS

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REFERENCES

[1] Harrington, J. D., Weselby, C., Veronico, N. A., and Hagenauer, B., "Nasa's airborne infrared observatory sees the "first light"." NASA press release 10-128 (May 2010).

[2] Becklin, E. E. and Gehrz, R. D., "Stratospheric Observatory for Infrared Astronomy (SOFIA)," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7453**, 745302 (Aug. 2009).

[3] Rosenthal, D., Beeman, J., Geis, N., Looney, L., Poglitsch, A., Park, W., Raab, W., and Urban, A., "16×25 Ge:Ga detector arrays for FIFI LS," in [*Airborne Telescope Systems*], Melugin, R. and Röser, H., eds., *Proc. SPIE* **4014**, 156–163 (2000).

[4] Poglitsch, A., Katterloher, R., Hönle, R., Beeman, J., Haller, E., Richter, H., Grözinger, U., Haegel, N., and Krabbe, A., "Far-Infrared Photoconductor Arrays for Herschel and SOFIA," in [*Millimeter and Submillimeter Detectors for Astronomy*], Phillips, T. and Zmuidzinas, J., eds., *Proc. SPIE* **4855**, 115–128 (2002).

[5] Raab, W., Looney, L., Poglitsch, A., Geis, N., Hönle, R., Rosenthal, D., and Genzel, R., "FIFI LS: the optical design and diffraction analysis," in [*Airborne Telescope Systems II*], Melugin, R. and Röser, H., eds., *Proc. SPIE* **4857**, 166–174 (2002).

[6] Looney, L., Raab, W., Poglitsch, A., and Geis, N., "Realizing Integral Field Spectroscopy in the Far-Infrared," *ApJ* **597**, 628–643 (2003).

[7] Stacey, G. J., Beeman, J. W., Haller, E. E., Geis, N., Poglitsch, A., and Rumitz, M., "Stressed and unstressed Ge:Ga detector arrays for airborne astronomy," *International Journal of Infrared and Millimeter Waves* **13**, 1689–1707 (Nov. 1992).

[8] Beeman, J. W. and Haller, E. E., "Ge:Ga photoconductor arrays: Design considerations and quantitative analysis of prototype single pixels," *Infrared Physics and Technology* **35**, 827–836 (Dec. 1994).

[9] Creten, Y., Charlier, O., Merken, P., Putzeys, J., and van Hoof, C., "A 4.2 K readout channel in a standard 0.7 μm CMOS process for a photoconductor array camera," *Journal de Physique IV* **12**, 203–206 (2002).

[10] Poglitsch, A., Waelkens, C., and Geis, N., "The Photoconductor Array Camera & Spectrometer (PACS) for the Far Infrared and Submillimetre Telescope (FIRST)," in [*UV, Optical, and IR Space Telescopes and Instruments*], Breckinridge, J. and Jakobsen, P., eds., *Proc. SPIE* **4013**, 221–232 (2000).

[11] Schweitzer, M., Poglitsch, A., Raab, W., Klein, R., Hönle, R., Geis, N., Genzel, R., Looney, L. W., Hamidouche, M., and Henning, T. K., "Verification of the optical system performance of FIFI-LS: the field-imaging far-infrared line spectrometer for SOFIA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7014**, 70140Z (Aug. 2008).

[12] Klein, R., Poglitsch, A., Raab, W., Geis, N., Hamidouche, M., Looney, L. W., Hönle, R., Schweitzer, M., Viehhauser, W., Genzel, R., Haller, E. E., and Henning, T., "FIFI LS: the far-infrared integral field spectrometer for SOFIA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6269**, 62691F (July 2006).

[13] Roellig, T. L., Becklin, E. E., Evans, N. J., De Buizer, J. M., Meixner, M., Tielens, A. G. G. M., Stacey, G. J., Vacca, W. D., Cuzzi, J. N., Backman, D. E., and SOFIA Science Vision Team, "The Science Vision for the Stratospheric Observatory for Infrared Astronomy (SOFIA)," *ArXiv e-prints* , 0905.4271 (May 2009).

[14] Henning, T., Klein, R., Launhardt, R., Lemke, D., and Pfau, W., "The molecular cloud core M17-North: ISO spectroscopy and IR/mm continuum mapping," *A&A* **332**, 1035–1043 (Apr. 1998).

[15] Heyminck, S., Güsten, R., Hartogh, P., Hübers, H., Stutzki, J., and Graf, U. U., "GREAT: a first light instrument for SOFIA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7014**, 701410 (Aug. 2008).

[16] Madden, S. C., Geis, N., Genzel, R., Herrmann, F., Poglitsch, A., Stacey, G. J., and Townes, C. H., "The interstellar medium of galaxies as seen through images of the 158 μm [CII] line," *Infrared Physics and Technology* **35**, 311–319 (Mar. 1994).