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SOFIA: first science highlights and future science potential

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SOFIA, the Stratospheric Observatory for Infrared Astronomy, is a joint project between NASA and the German Aerospace Agency (DLR) to develop and operate a 2.5 m airborne telescope in a highly modified Boeing 747SP aircraft that can fly as high as 45 000 feet (13.7 km). This is above 99.8 % of the precipitable water vapor which blocks much of the mid- and far-infrared radiation from reaching ground-based telescopes. In this review, we briefly discuss the characteristics of the Observatory and present a number of early science highlights obtained with the FORCAST camera in 5–40 micron spectral region and with the GREAT heterodyne spectrometer in the 130–240 micron spectral region. The FORCAST images in Orion show the discovery of a new high-mass protostar (IRc4), while GREAT observations at 1 km s^{-1} velocity resolution detected velocity-resolved, redshifted ammonia spectra at 1.81 THz in absorption against several strong far-infrared dust continuum sources, clear evidence of substantial protostellar infall onto massive (non-ionizing) protostars. These powerful new data allow us to determine how massive stars form in our Galaxy. Another highlight is the stunning image taken by FORCAST that reveals the transient circumnuclear 1.5 pc radius (dust) ring around our Galactic center, heated by hundreds of massive stars in the young nuclear star cluster. The GREAT heterodyne spectrometer also observed the circumnuclear ring in highly excited CO rotational lines, indicative of emission from warm dense molecular gas with broad velocity structure, perhaps due to local shock heating. GREAT also made superb mapping observations of the [C II] fine structure cooling line at 158 microns, for example in M17-SW molecular cloud–star cluster interface, observations which disprove the simple canonical photodissociation models. The much better baseline stability of the GREAT receivers (compared to *Herschel* HIFI) allows efficient on-the-fly mapping of extended [C II] emission in our galaxy and also in other nearby spiral galaxies. Of particular note is the GREAT discovery of two new molecules outside the solar system: OD (the deuterated OH hydroxyl radical) as well as mercapto radical SH, both in absorption near 1.4 THz, a frequency gap where *Herschel* was blind. A special highlight was the 2011 June 23 UT stellar occultation by Pluto using the HIPO high speed photometer and the FDC fast diagnostic camera. This difficult but successful observation, which was both space-critical (within 100 km) and time-critical (within 1 min), proved that SOFIA can be in the right place at the right time, when important transient events occur.

1 What is SOFIA?

SOFIA is short for “Stratospheric Observatory for Infrared Astronomy”. SOFIA is a substantially modified Boeing 747SP (SP = special purpose) aircraft that carries a ∼20 ton gyro-stabilized telescope in its rear fuselage (Fig. 1) with a mirror diameter of 2.7 m (2.5 m clear aperture), similar in size to the Hubble Space Telescope. Yet while Hubble in orbit observes in the UV, optical, and near-infrared part of the electromagnetic spectrum, SOFIA mainly observes and excels in the mid- and far-infrared (30–300 microns, but see below). These wavelengths represent radiation coming from cool ($T = 10$ K) to warm ($T = 100$ K) celestial objects, both interstellar gas and dust, that would not reach ground-based observing sites, as they would be absorbed by significant amounts of water vapor in the atmosphere. SOFIA typically flies at altitudes of 41 000 to 45 000 ft (12–13.7 km), i.e. above 99.8–99.9 % of the precipitable water vapor (Stutzki 2006; Becklin & Gehrz 2009). The first SOFIA open door flight took place in December 2009 and the first SOFIA science flight in December 2010 (with FORCAST).

SOFIA is a bi-lateral project between NASA and the German Aerospace Agency DLR, with the US side being the major partner (80 %) and Germany the minor partner (20 %). The percentages refer to the share of the total cost including maintenance and fuel, and indeed also to the ratio of observing time between the two countries. In essence, NASA provided the aircraft (including the modifications) while DLR paid for the design and installation of the telescope. NASA runs the programme through its subcontractor USRA (Universities Space Research Association), while DLR assigned the task to Deutsches SOFIA Institute (DSI) at Raumfahrtzentrum at University of Stuttgart (through a renewable 4 year contract). The SOFIA plane operates out of NASA-Dryden Airforce Operations Facility (DAOF) in Palmdale, Southern California (1 hour north of Los Angeles), while the SOFIA Science Center is located at NASA-Ames, Moffett Field in Northern California (1 hour south

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of San Francisco). Of the 280 or so people that work on SOFIA, 250 are from NASA and USRA and support contractors, about 30 are at the DSI (and a few at DLR). Twelve of the German DSI staff are currently delegated to the DAOF in Palmdale, and five to NASA-Ames in Moffett Field. The numbers will increase when SOFIA is ramping up to its full operational capability, which ultimately aims for up to 960 flight hours per year (some time after 2015) for a projected 20 year lifetime (Hall et al. 2012).

SOFIA is primarily a star formation and interstellar medium observatory. It is a key facility for studying the dynamics and energetics in regions of star formation (e.g. cloud collapse) as well as astrochemical processes in the interstellar medium (ISM), including molecular rotational excitation. Observations of dusty optically obscured sources (spectral energy distributions) and time critical investigations of transient events (e.g. occultations of solar system objects) are also important. A more detailed account and some examples will be given in Sect. 5.

SOFIA can be upgraded continually and be used as a test bed for state-of-the-art and high-risk technologies in an environment that has conditions close to those encountered in space flight. Currently, in the present Cycle 1 call for observing proposals, SOFIA offers 4 instruments (FORCAST, GREAT, FLITECAM, and HIPO – see Table 1), while in Cycle 2 (to be flown in calendar year 2014) two more instruments (FIFI-LS and EXES) will be commissioned. Cycle 2 proposals are due by the end of June 2013 with a total of ∼200 open time science flight hours for the US/German astronomical community, including international proposals. SOFIA will be a training ground for a new generation of instrumentalists and experimental astronomers. Also, education and public outreach have historically been important aspects of NASA's airborne astronomy program, and SOFIA's design provides for flying educators on board who can involve their students in the excitement of scientific research.

2 Why SOFIA?

The basic reason for airborne astronomy is to avoid atmospheric absorption for mid- and far-infrared observations. Such observations are key to the study of the warm and cold phases of the life cycle of the interstellar medium (ISM), including heating and cooling, formation and feedback of massive and intermediate-mass stars (e.g. Wiesemeyer 2012, in German). Most of the energy of star forming regions, external galaxies, and cool objects in the Universe is in the far-infrared part of the spectrum, and the most important cooling lines in the ISM also fall in this spectral region (e.g. [C II] at 158 microns or [O I] at 63 microns).

SOFIA flies at altitudes as high as 45 000 feet (13.7 km), above 99.8 % of the remaining atmospheric water vapor. At this altitude, the precipitable atmospheric water typically has a column depth of less than 10 μm, 20 times lower than at the best terrestrial sites (e.g. ALMA and CCAT in Chile or Dome C and Dome A in Antarctica) and 50–100 times lower than at good terrestrial sites (Mauna Kea). The atmospheric transmission averages 80 % or higher across SOFIA's wide wavelength range (particularly in the far-infrared range from 30 to 300 microns). SOFIA has access to large parts of the electromagnetic spectrum that are completely blocked to ground-based telescopes (see Fig. 2). Although some strong water absorption lines remain, giving the transmission curve the appearance of a "picket fence", spectroscopy can be done between the water lines. Enough flux is transmitted between the pickets in many regions of the spectrum to permit wide-band photometry (see Tremblin et al. 2012).

It was already decades ago that some astronomers realized there would be merit and major advantages to do airborne astronomy in the stratosphere. The Kuiper Airborne Observatory was one of the first successful long-term endeavors exploiting those advantages in the far-infrared part of the spectrum. It flew from 1974 to 1995. SOFIA is its successor. Although it took a long time to get SOFIA off the ground and airborne, and although at first sight it may seem it was overtaken by the recent spectacular results of the *Herschel* Observatory, a closer look reveals that it is a perfect follow-up and complement to the *Herschel* Space Telescope. There are many questions that *Herschel* has touched upon which remain unanswered. Yet *Herschel* has whetted the appetite of the far-infrared astronomical community that we can expect that the *Herschel* users will become the SOFIA users, now that *Herschel* ran out of cryogen to cool its detectors and will be unable to continue observations (since end of April 2013).

Apart from the remaining small amount of atmospheric water vapor, which to first order prevents or limits observing astronomical water lines, flying in the stratosphere is almost as good as observing from space. The advantage is that, unlike a space satellite, an observatory like SOFIA can come home every night allowing to fix potential problems and also to readily change instruments for more flexible observing sequences. The SOFIA Observatory also has a much longer lifetime than any infrared space platform (e.g. *Herschel*, *Spitzer*, WISE, except HST). After *Herschel*, SOFIA will be the premier far-infrared observatory in the world for many years to come (at least for a decade). Only the Japanese 3.5 m actively cooled SPICA space telescope, if it is going ahead which is at present unclear, will rival SOFIA, perhaps in 10 years time. However, let us be reminded that SOFIA with very high-resolution spectroscopic instruments like GREAT and EXES is not suffering from excess sky background, i.e. SOFIA in such high-resolution spectroscopic mode is indeed quasi a space telescope.

SOFIA has enormous synergies with CCAT (similar diffraction-limited angular resolution at the respective wavelengths, e.g. 60 microns for the 2.5 m SOFIA telescope vs. 600 microns for the 25 m CCAT dish). It also is complementary to ALMA and ALMA star formation science. ALMA in the submm can follow-up SOFIA mid- and far-

Fig. 1 The SOFIA B747SP aircraft with open door flying over the Sierra Nevada in California (photo NASA).

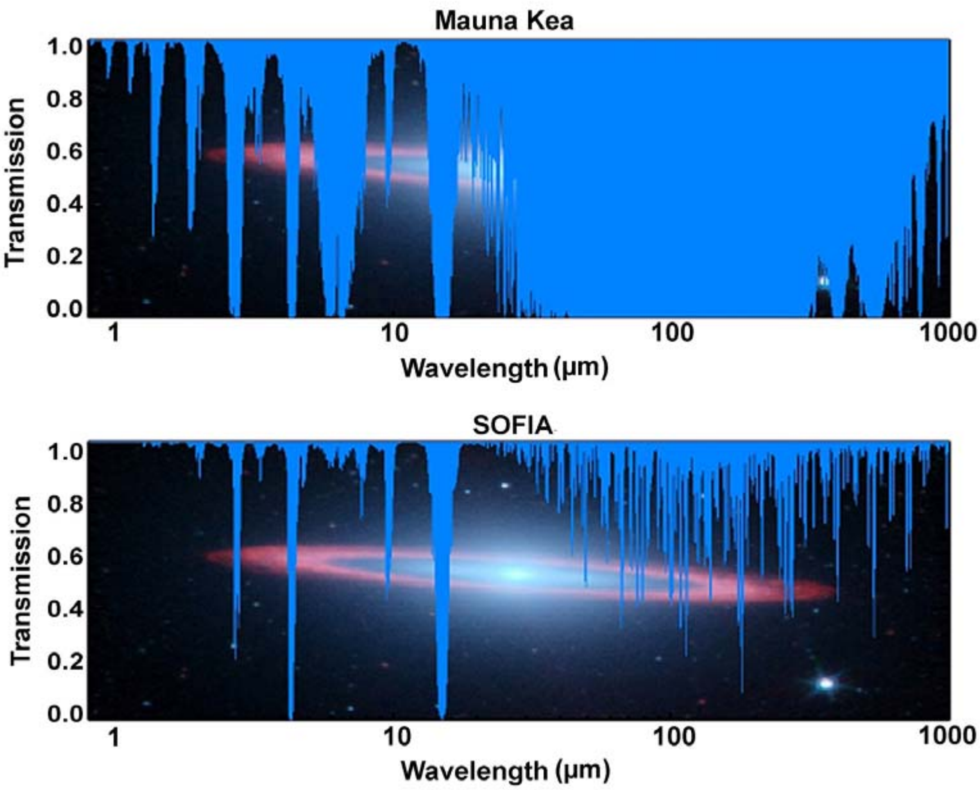

Fig. 2 Comparison of atmospheric transmission in the infrared (1 to 1000 microns) for SOFIA in the stratosphere and the Mauna Kea ground-based observing site (figure taken from The Science Vision of SOFIA, NASA-Ames 2009).

infrared observations at much higher angular resolution, especially in crowded regions; while SOFIA can complement ALMA submm data in the mid- and far-infrared for sufficiently isolated sources.

3 The SOFIA Observatory, telescope, and instruments

3.1 The SOFIA Observatory and operational range

The SOFIA aircraft, called Clipper Lindbergh, will normally be staged out of the Dryden Aircraft Operations Facility (DAOF) at Palmdale Municipal Airport (KPMD) in Palmdale, California, but will operate from other airports around the world when necessary for scientific reasons. Southern hemisphere bases will be used for observations of targets at extreme southerly declinations. SOFIA's deployment flexibility will allow measurements of transient events that are visible only at particular locations (e.g., stellar occultations) and for observations of objects that are at extreme declinations (e.g. the Magellanic Clouds). Flights will be as long as 10.5 hours with as much as 8–8.5 hours being available for time on science targets. The rapid turn-around time between flights will facilitate timely observations of transient events such as variable stars, comet apparitions, occultations, and nova and supernova explosions.

SOFIA is an observatory, in fact one of NASA's Great Observatories, and thus in the same class as HST, *Chandra*, and *Spitzer*. The fact that SOFIA is an observatory means that it is accessible to everyone, not only US and German scientist but all over the world. Accessible means everyone can propose, get his/her data pipeline-reduced, and can later use the data archive. This is unlike SOFIA's predecessor, the Kuiper Airborne Observatory or KAO (1974–1995) which was operated quite differently in the sense that it was mostly run by principal investigator (PI) teams who brought their own instruments and that any guest investigator had to cooperate with the PI teams. The KAO also had a three times smaller mirror (91 cm diameter), located in the front part of a C141 aircraft, and hence a three times poorer spatial resolution in the diffraction-limited far-infrared wavelength regime. Like the KAO in the past, SOFIA will also deploy to the Southern Hemisphere.

3.2 The SOFIA telescope and image quality

The telescope, supplied by the DLR as a German contribution to the development of SOFIA, is a bent Cassegrain with a 2.7 m (2.5 m effective aperture) parabolic primary mirror and a 0.35 m diameter hyperbolic secondary mirror. A gold-coated dichroic and an aluminum-coated flat feed two f/19.6 Nasmyth foci (the IR science focus and a visible light focus for guiding), about 300 mm behind the instrument flange. The secondary mirror provides chop amplitudes of up to ± 4 arcminutes between 0 and 20 Hz. The 2.7 m diameter of the primary mirror allows an unvignetted 2.5 m aperture to illuminate the entire focal plane over the entire range of chop angles. The visible beam is fed into an optical Focal Plane Imager (FPI) used for fine guiding using the focal plane image. Two other optical imaging and guiding cameras, the Wide Field Imager (WFI) and the Fine Field Imager (FFI), are attached to the front ring of the telescope to assist with acquisition and for guiding when no visible images are available in the focal plane. The telescope is mounted in an open cavity in the aft section of the aircraft and views the sky through a port-side 4.5 m $\times$ 6 m doorway *on the left side of the plane*. The telescope is moved by magnetic torquers around a spherical bearing through which the Nasmyth beam is passed. The focal plane instruments and the observers are on the pressurized side of the 21.3 feet diameter bulkhead on which the spherical bearing is mounted, allowing a shirt-sleeve working environment for the researchers and crew (for a schematic view of the inside of the aircraft, see Fig. 3; while Fig. 4 is a snapshot taken during a SOFIA early science observing flight).

The telescope has an unvignetted elevation range of 20–60 degrees. Since the cross-elevation range is only a few degrees, most of the azimuthal telescope movement required during tracking must be provided by changing the airplane's heading. This requirement also dictates that the flight plan is determined by the list of targets to be observed. For flights that take off and land from the same field, some fraction of the targets must be located to the north since the telescope can only view from the port-side of the aircraft. A single target can be viewed for an entire flight by flying one-way flights between widely separated airfields. Flight planning is a tricky business, where many pieces of a puzzle must be combined. A useful white paper on the challenges and intricacies of flight planning authored by Randolf Klein and B. G. Andersson (both USRA) can be found on SOFIA's observers handbook, which includes sample flight plans (www.sofia.usra.edu/Science/ObserversHandbook/). An example of a recent GREAT flight plan is shown in the Appendix.

The image quality currently obtained in SOFIA observations is about 2.5 arcsec FWHM, mainly due to jitter[1] from the telescope caused by the air flow into the cavity. To this, one has to add (in quadrature) the diffraction which for SOFIA's 2.5 m telescope is about 1/10 (in arcsec) of the wavelength (in microns), i.e. 2.5 arcsec at 25 microns. In total, this then yields 3.5 arcsec FWHM at 25 microns. Similarly, we obtain a total image size of 4.0 arcsec FWHM at 35 microns. This may be compared to the FORCAST pixel size which is 0.75 arcsec and shows that the point-spread function is well-sampled. Improvements of the image quality over the next four years will likely make the point-spread function (including diffraction) as good as 2.5 arcsec FWHM at 20 microns. Shear layer seeing (air flow over the cavity) is negligible at the longer mid-IR and far-

[1] The jitter ($<$90 Hz) for the most part is due to the eigenfrequencies of the telescope assembly (TA) and is limited in amplitude by the inertia (heavy weight) of the TA, assisted by negative feedback from force motors

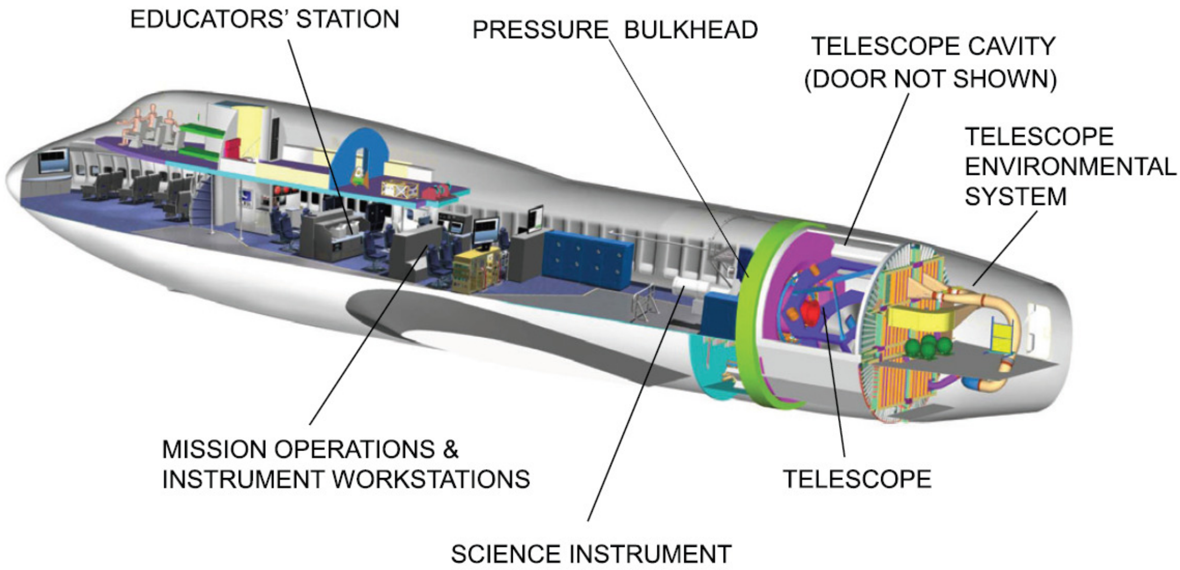

Fig. 3 Schematic view of the SOFIA observatory showing the pressurized cabin to the left of the pressure bulkhead, and the ambient telescope cavity with its port-side open-door viewing window. An environmental control system aft of the telescope cavity prevents condensation when the door is closed. Reproduced by permission of Young et al. (2012) and the American Astronomical Society.

Fig. 4 Working environment onboard SOFIA during the first early science flight with FORCAST. Terry Herter (center right, in charge, standing at the PI rack). The FORCAST instrument is mounted at the Nasmyth focus and the telescope counterweight structure can be seen at the far end at an elevation angle of about 20 degrees. Photo USRA gallery.

Table 1 SOFIA first generation instrument summary.

Name	Description	PI	Institution	Wavelengths (μm)	Spectral Resolution
FORCAST	Mid-Infrared Camera and Grism Spectrometer	T. Herter	Cornell	5–40	200
GREAT	Heterodyne Spectrometer	R. Güsten	MPIfR	60–240	10^6–10^8
FLITECAM	Near-Infrared Camera and Grism Spectrometer	I. McLean	UCLA	1–5	2000
HIPO	CCD Occultation Photometer	T. Dunham	Lowell Obs.	0.3–1.1	
EXES	Mid-Infrared Spectrometer	M. Richter	UC Davis	5–28	3000, 10^4, 10^5
FIFI-LS	Integral Field Far-Infrared Spectrometer	A. Krabbe	U. Stuttgart	42–210	1000–3750
HAWC+	Far-Infrared Camera (and polarimeter)	D. Dowell	JPL	50–250	

IR wavelengths, but can be up to 5 arcsec in the optical and less in near-infrared. Pointing of the SOFIA telescope is accurate to about 0.5 arcsec and the tracking is good, also 0.5 arcsec over a timespan of half an hour to an hour. This is important to know in case of observations (e.g. with GREAT) when no offset guiding is available.

3.3 SOFIA's first and second generation instruments, sensitivity, and spatial resolution

Table 1 summarizes the operational characteristics of SOFIA's seven first generation Science Instruments (SIs). These include three Facility Class Science Instruments (FSIs) that will be maintained and operated by the SOFIA Science Mission Operations (SMO) staff: the Faint Object InfraRed Camera for the SOFIA Telescope (FORCAST), the First Light Infrared Test Experiment CAMera (FLITECAM), and the High-resolution Airborne Wideband Camera (HAWC). The latter has been replaced by the second generation instrument HAWC+ which will include an imaging polarimetric capability (to be commissioned in Cycle 3). Second generation instrument development on the German side is underway and funded. It is led by MPIfR/Bonn and will introduce upGREAT, a 1.9 to 2.5 THz heterodyne spectrometer array with $2{\times}7$ pixels on the sky (also in Cycle 3). This will increase the mapping efficiency considerably. FSI pipeline-reduced and flux calibrated data from these SIs will be archived for general access by the astronomical community after a one year exclusive access (proprietary) period.

Four out of the seven SIs are Principal Investigator (PI) class instruments maintained and operated by the PI teams at their home institutions, although FIFI-LS will be transferred to the SMO Center sometime in 2014 and subsequently operated as an FSI. FIFI-LS data will be pipeline-reduced and flux-calibrated before it is placed in the SOFIA data archive. General investigators will be able to propose for PI instruments in collaboration with the PI team. Plans are for pipeline-reduced data from the US PI instruments to be added to the science archive after a one year exclusive access period. The two PI-class instruments under development in the US are the Echelon-Cross-Echelle Spectrograph (EXES) and High-speed Imaging Photometer for Occulations (HIPO). PI-class instruments being developed in Germany are the German Receiver for Astronomy at Terahertz Frequencies (GREAT) and the Field Imaging Far-Infrared Line Spectrometer (FIFI-LS). Detailed information about the first-generation SIs and their operation is available at http://www.sofia.usra.edu/Science/instruments/index.html.

Given the IR background associated with SOFIA's flight environment, the first generation SIs on the 2.5 m telescope is capable of measurements with an order of magnitude better photometric sensitivity than IRAS and three times better linear spatial resolution than the *Spitzer* Space Telescope. SOFIA's sensitivity is comparable to that of the European Space Agency (ESA) Infrared Space Observatory (ISO). SOFIA's capability for diffraction-limited imaging beyond 20 μm will produce the sharpest images of any current or planned IR telescope operating in the 30 to 60 μm region. The SI exposure time calculators on the SOFIA website (see http://www.sofia.usra.edu/Science/instruments/ and http://great.sofia.usra.edu) will enable prospective observers to evaluate the feasibility of proposed observations.

4 Early science statistics and Cycle 1 and 2 schedule

SOFIA acquired its first light infrared (IR) images with the FORCAST camera on May 26, 2010 UT. Six early science flights were conducted with FORCAST and GREAT during December 2010–April 2011. A call for the Basic Science Program released on April 19, 2010 resulted in sixty unique proposals requesting a total of 234 hours for FORCAST and 42 hours for GREAT. The proposals were reviewed for scientific merit during fall, 2010 and 52.1 and 17.4 hours of time were awarded for FORCAST and GREAT respectively. The Basic Science flight series of ten FORCAST flights, one HIPO observation of an occultation of Pluto, and thirteen GREAT flights began in May 2011 and concluded in November 2011. Thirty papers from the Early and Basic Science program have been published, eight papers on FORCAST science in a special edition of the Astrophysical Journal Letters (2012, Vol. 749) and twenty-two on GREAT science have appeared in a special edition of Astronomy and Astrophysics (2012, Vol. 542).

Cycle 1 proposals were due on January 27, 2012 on the US side and on March 2, 2012 on the German side. 172 unique proposals were received (133 US; 39 German). Proposal selections were announced in July 2012. The oversubscription was about a factor of 5, both on the US and

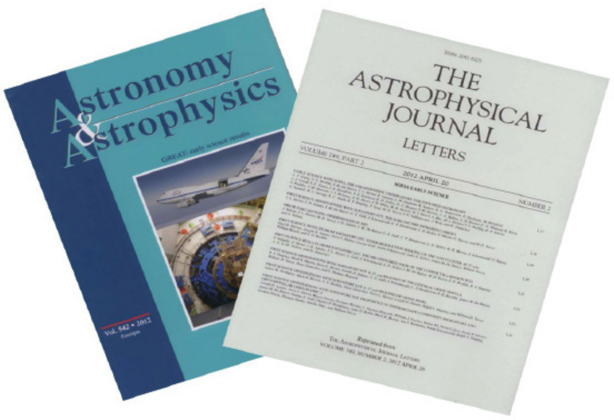

Fig. 5 Special issues of ApJ Letters Vol. 749 (April 2012) and Astronomy & Astrophysics Vol. 542 (June 2012) where the respective early science results of FORCAST and GREAT have been published.

the German side. A glass cockpit has been installed in the aircraft to bring the avionics up to state-of-the-art standards and improvements to the Mission Controls and Communications System (MCCS) were made. Due to delays in completing the avionics upgrade and problems with the MCCS software, Cycle 1 observations only began in April 2013 (with GREAT, followed by FORCAST in May) and will continue through November, with a 3 week deployment to the southern hemisphere (Christchurch, New Zealand) in July 2013 (with GREAT only observations).

Cycle 2 observations will occur in 2014 and Cycle 3 observations in 2015. The flight frequency will ramp up to an expected normal operational level of some one hundred 8–10 hour scientific flights per year by 2015, implying a challenging flight rate of 4 flights a week (beginning towards the end of Cycle 2). The SOFIA Program is planned to last through the mid 2030's.

5 Early science highlights with SOFIA

The broad wavelength window of the SOFIA instrument suite (see Table 1) is a unique advantage of the SOFIA Observatory and allows us to cover a huge range of observational astronomy, from planetary science to star forming regions and from the Galactic Center regions in our galaxy to the ISM in nearby starburst galaxies, i.e. almost everything except cosmology. Here we discuss some of the early science highlights (see also Becklin et al. 2012; Wiesemeyer 2012).

5.1 FORCAST images and GREAT spectra of regions of star formation

Giant molecular clouds (GMCs) in the interstellar medium (ISM), the birth sites of new stars and the repositories for the ejecta from dying stars, are engines that drive the chemical evolution of the Galaxy. Young stars are born by gravitational contraction in GMC cores. As stars age, the winds from low-mass, asymptotic giant branch stars (AGB) and high-mass, red supergiants (RSG), novae, and supernovae inject products of main sequence astration and explosive nucleosynthesis into the ISM, increasing the metallicity of the material incorporated into the next generation of stars. Understanding the physics of star formation is crucial to determining how this cycle of galactic chemical enrichment proceeds. Imaging and spectroscopic observations during early science flights by FORCAST and GREAT are already providing new information about the star formation process in GMCs. In the future, far-IR polarization measurements with SOFIA HAWC will enhance our understanding of the way in which magnetic fields determine the evolution of protostellar objects in massive star forming regions by probing the warm, dense material in the cores of GMCs.

5.1.1 FORCAST images of the Orion Nebula

Shuping et al. (2012) used the FORCAST camera to image the central region of the Orion Nebula. These 4 arcsec images are the highest resolution images ever obtained of this region at 37.1 μm (Fig. 6, bottom right). The Becklin-Neugebauer/Kleinmann-Low (BN/KL) protostar complex dominates the IR emission from the region and consists of a cluster of self-luminous objects. The BN protostar is the brightest of these at short wavelengths, but the cluster of sources to the south far outshines it at 37.1 μm. The short wavelength images confirm that the Ney-Allen (NA) nebula is a crescent-shaped feature first discovered by Robberto et al. (2005) displaced 2.2 arcsec to the southwest of θ^1 D Ori. The spatial morphology of NA is consistent with it being ambient dust swept up by the stellar wind from θ^1 D Ori. The FORCAST images also detect emission from several "proplyds" (proto-planetary disks) and embedded young stellar objects (YSOs) such as IRc9. Spectral energy distribution (SED) models presented by Shuping et al. for IRc 9 give a bolometric luminosity of 110–215 solar luminosities and suggest that IRc 9 is the progenitor of a 3–4 solar mass zero-age main-sequence star surrounded by a small circumstellar disk ($<$100 AU) that generates the 3 to 10 μm flux and a large circumstellar envelope ($R >$ 2700 AU) that dominates the SED at the long wavelengths. Shuping et al. attribute the diffuse, nebular IR component to thermal emission from the background photodissociation region (PDR) and suggest that the spatial variations in the diffuse emission are caused by billowing and density fluctuations at the surface of the PDR.

5.1.2 The BNKL protostars

The BNKL protostar complex in the Orion Nebula is the closest region of high-mass star formation in the Galaxy, and has been studied at many wavelengths. It is highly obscured at visual wavelengths and is brightest at infrared and

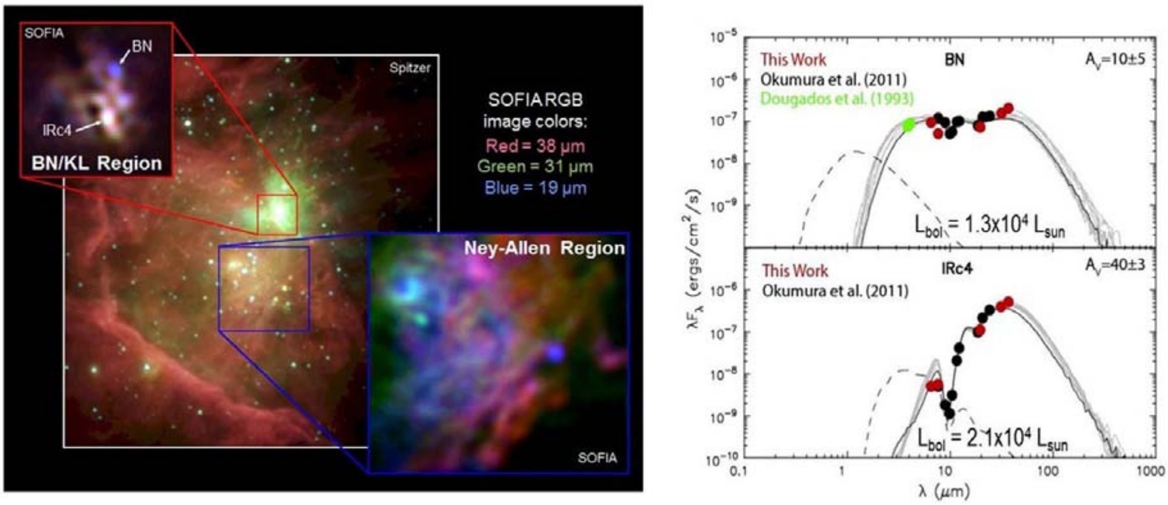

Fig. 6 The Orion Nebula Cluster imaged by FORCAST on SOFIA (from Shuping et al. 2012 and De Buizer et al. 2012), including spectral energy distributions of the two main protostars in the BNKL region (*right*, De Buizer et al. 2012). Figure courtesy of J. De Buizer (2012).

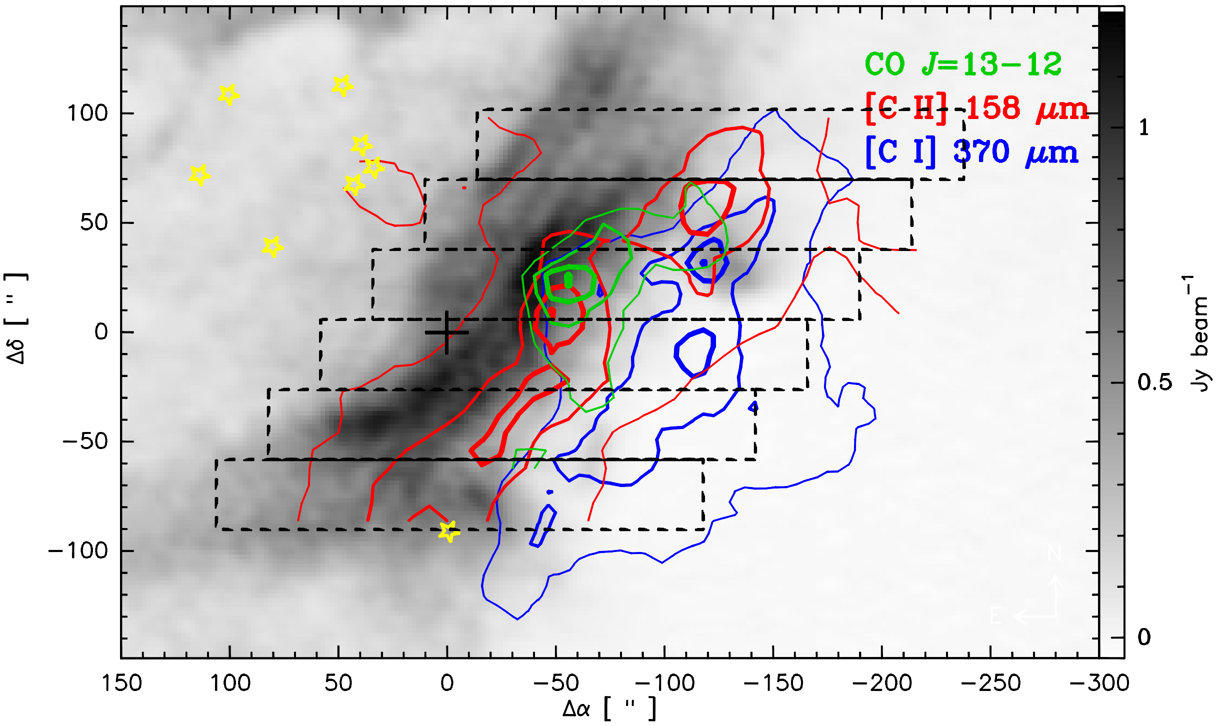

Fig. 7 GREAT map of the M17-SW photodissociation region. Contours of the velocity integrated emission of ^{12}CO $J = 13$–12 (green), [C II] (red), and the [C I] $^3P_2$–$^3P_1$ 370 micron from APEX (blue, integrated in 9–30 km s^{-1}) are overlaid on the VLA 21 cm continuum emission (Brogan & Troland 2001). The contour levels (from thin to thick) are 50 %, 75 %, and 90 % of the peak emission. The stars indicate the O and B ionizing stars (Hanson et al. 1997; Chini & Hoffmeister 2008). Dashed frames depict the GREAT beam center for the edges of the six on-the-fly-strips. Contour maps are smoothed to 20″ resolution. Figure reproduced from Perez-Beaupuits et al. (2012), with permission.

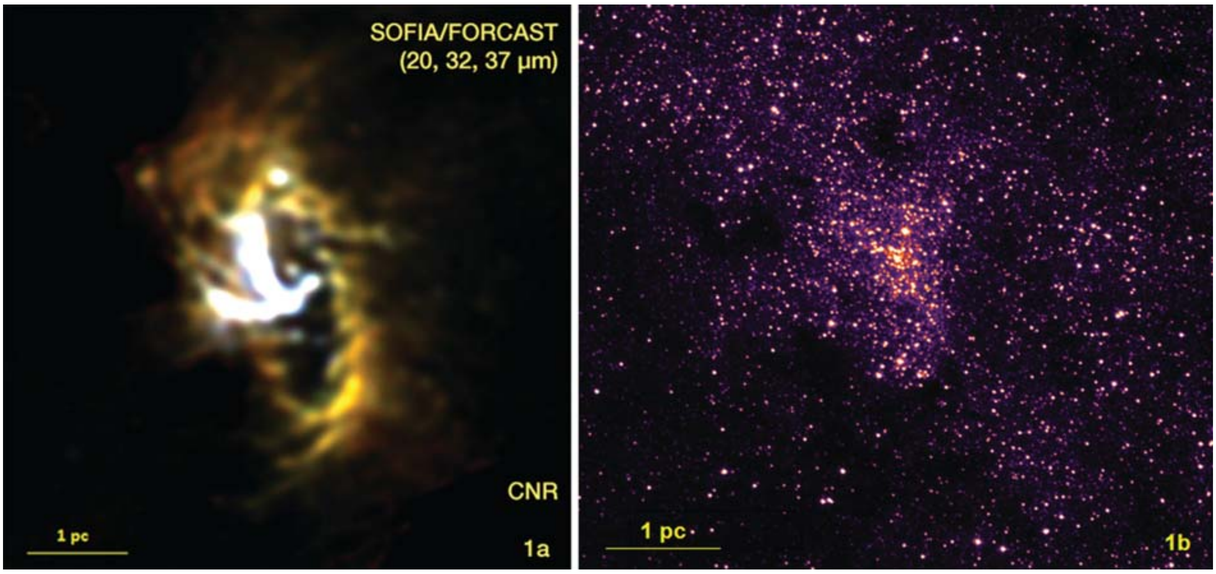

Fig. 8 Image release at the AAS in Long Beach (Lau et al. 2013, January 8): Galactic center circumnuclear ring as imaged by FORCAST/SOFIA (*left*) and NICMOS/HST (*right*) with the same field-of-view; see text for details.

submillimeter wavelengths. De Buizer et al. (2012) used FORCAST on SOFIA to obtain 5–40 μm images of the entire BN/KL complex (Fig. 6, top left). The 4 arcsec spatial resolution 31.5 and 37.1 μm images are the most detailed observations ever obtained of this region at long IR wavelengths. They show that that the BN object is declining in brightness beyond 19.7 μm and that IRc4 is the brightest source at 31.5 and 37.1 μm. De Buizer et al. conclude from its brightness and color temperature that IRc4 is evidently self-luminous, demonstrating that the BNKL object is likely a cluster of massive protostars rather than a single protostar heating the surrounding dust. They also report the discovery of a new 31.5–37.1 micron source (SOF 1) spatially coincident with the northeastern outflow lobe from the protostellar disk associated with radio source I.

5.1.3 GREAT detection of in-falling gas in a massive protostellar object

Massive star formation is associated with ultra-compact H II regions, dense clumps in the cores of giant molecular clouds. SOFIA GREAT observations of this critical, highly obscured phase of massive star formation have been made by Wyrowski et al. (2012). They used the optically thick ammonia (NH_3) 3_{2+}–2_{2-} absorption line at 1810.379971 GHz to observe the protostellar infall of the three compact cloud cores, including the ultra-compact H II region G34.26+0.15 (see Fig. 9). This line has the same lower level as the optically thin centimeter inversion line at 23.7 GHz observed in emission by Churchwell et al. (1990). It is evident that only the red wing of the absorption line is seen against the dust emission continuum, a strong indication that the cloud is in a state of contraction. The velocity width of the 23.7 GHz line is consistent with the full velocity width that is associated with optically thin lines that also measure the blue wing associated with the infall. Similar evidence for protostellar infall was seen in W43-MM1 and G31.41+0.31.

5.2 GREAT [C II] maps of the M17-SW molecular cloud

M17-SW is a giant molecular cloud at a distance of $\sim$2 kpc, illuminated by an obscured cluster of many OB stars (Chini & Hoffmeister 2008). Its nearly edge-on geometry make M17-SW one of the best studied prototypes of clumpy photon-dominated region (PDR) molecular cloud interface in the Galaxy. It was observed and successfully mapped on-the-fly in [C II] (1.91 THz, 158 micron) and CO $J = 13$–12 (1.50 Thz, 200 micron) on the first GREAT short science flight in April 2011. Figure 7 shows the map of the velocity integrated emission of C+ and CO $J = 13$–12, compared to the neutral carbon emission at 370 microns from APEX (Perez-Beaupuits et al. 2012). The map indicates that the standard PDR spatial emission sequence C+ $\rightarrow$ C $\rightarrow$ CO (Tielens & Hollenbach 1985ab) does not hold. Indeed, the total integrated C+ emission peaks at the interface between the neutral H I (seen in 21-cm continuum) and the molecular cloud in the west and drops towards the H II region (star cluster) in the east. The high-J hot CO emission emerges from a dense region between the ionised and neutral carbon emission. The integrated intensity maps do not reveal the origin of the emission lines, only narrow-velocity channel or strip maps can. Making use of GREAT's velocity resolution and spatial resolution (smoothed to 1 km s^{-1} and 20$''$, respectively), the different emission components can be disentangled. The result is that the clumpy PDR model (Stutzki & Guesten 1990) can explain the data, if a large fraction of foreground C+ emission, unrelated to the M17-SW cloud, is subtracted. Dominant internal heating by massive embeddded stars can also suppress any classical PDR

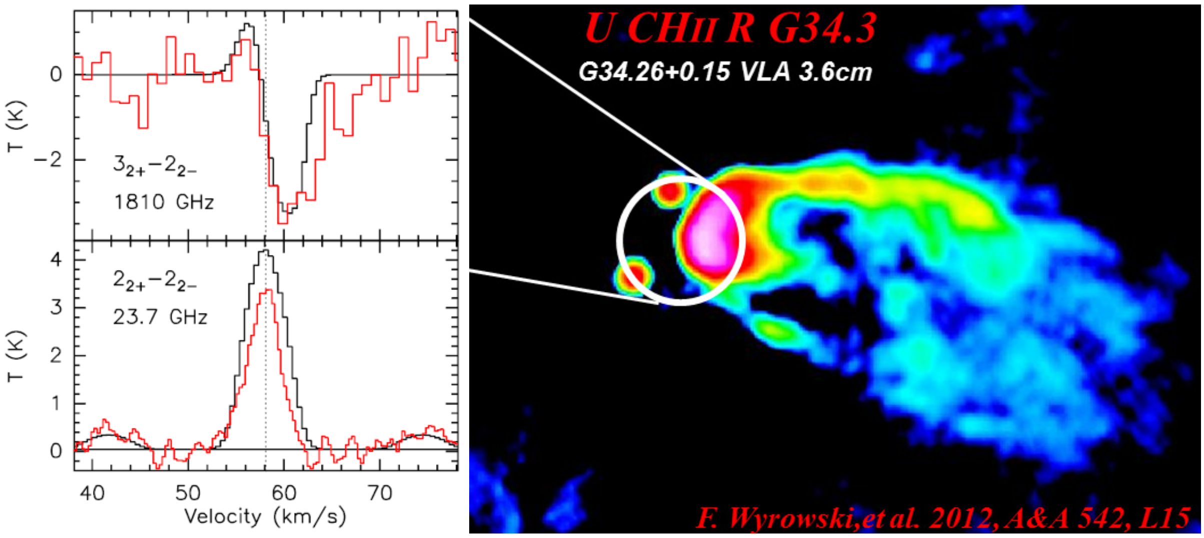

Fig. 9 *Left*: red lines are G34.26+0.15 NH_3 spectra as measured using SOFIA (*top left*) and the Effelsberg 100 m dish (*lower left*) from Churchwell et al. (1990). Black lines refer to the RATRAN model discussed by Wyrowski et al. (2012). The velocity of the center of mass of the system from $C^{17}O$ is indicated by a dotted line. Reproduced by permission of Wyrowski et al. (2012). *Right*: position of the GREAT beam is shown against a 3.6 cm VLA image (after van Buren et al. 1990).

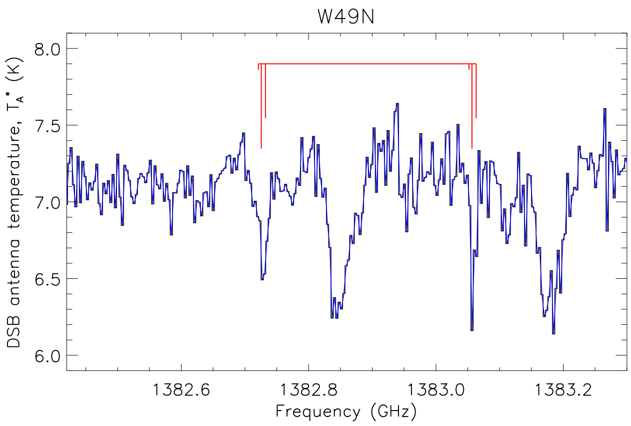

Fig. 10 Spectrum of SH $^2\Pi_{3/2} J = 5/2 \leftarrow 3/2$ Λ doublet obtained by GREAT toward W49N. Note that because GREAT employs double sideband receivers, the complete absorption of radiation at a single frequency will reduce the measured antenna temperature to one-half the apparent continuum level. The lambda doubling and hyperfine splittings are indicated by the red bars for a component at an LSR velocity of 40 km s^{-1} (Neufeld et al. 2012, with permission).

stratification. It is important to note that concentrated C+ far-infrared emission may actually trace embedded hydrogen non-ionising B-stars instead of hydrogen-ionising embedded O-stars and H II regions (Schneider et al. 2012).

5.3 FORCAST observations of the Galactic Center circumnuclear ring

The observation of the circumnuclear ring (or disk) in the Galactic center that is orbiting the central massive black hole at a radius of about 1.5 pc is one of the more spectacular results that SOFIA/FORCAST have produced. The image shown in Fig. 8 (left) captures an inclined cloud of gas and dust at 20, 32, and 37 microns (color composite, with 37 micron radiation seen in red and 20 micron radiation seen in blue). There is a color or temperature gradient across the thickness of the ring, with the inner part of the ring being hotter (bluer). The bulk of the emission is continuum radiation from dust at a mean temperature of about 100 K (more details are given in Lau et al. 2013, submitted). The heating of the dust ring is due to the UV radiation from a multitude of OB stars (a young nuclear star cluster with an age about 4–6 Myr) inside the region circled by the ring. The heating is not due to radiation associated with the black hole. The bright Y-shaped feature in the image is believed to be material falling from the ring towards the black hole which is located where the arms of the "Y" intersect. Perhaps the ring originally was a disk that reached close to the central black hole in the past and formed the nuclear star cluster (although this model of star formation near the Galactic Center has its own problems, associated with the issue that prestellar cores would need to be extremely dense to survive tidal disruption). Perhaps the ring of gas and dust is a periodic phenomenon of self-regulated star formation (M. Morris, priv. comm.). The RHS of Fig. 8 (right) shows a NICMOS near-infrared image with the same field-of-view, same scale, and the same orientation. At this wavelength (1.9 microns) dust extinction in the Milky Way is hiding features that are seen in the SOFIA image. In contrast, the stars in the HST image emit mostly visibly and near-infrared radiation and thus are not seen in the SOFIA mid-infrared image. Extra dense concentrations of dust associated with the circumnuclear ring explains the patches of apparently lower star density in the near-infrared image.

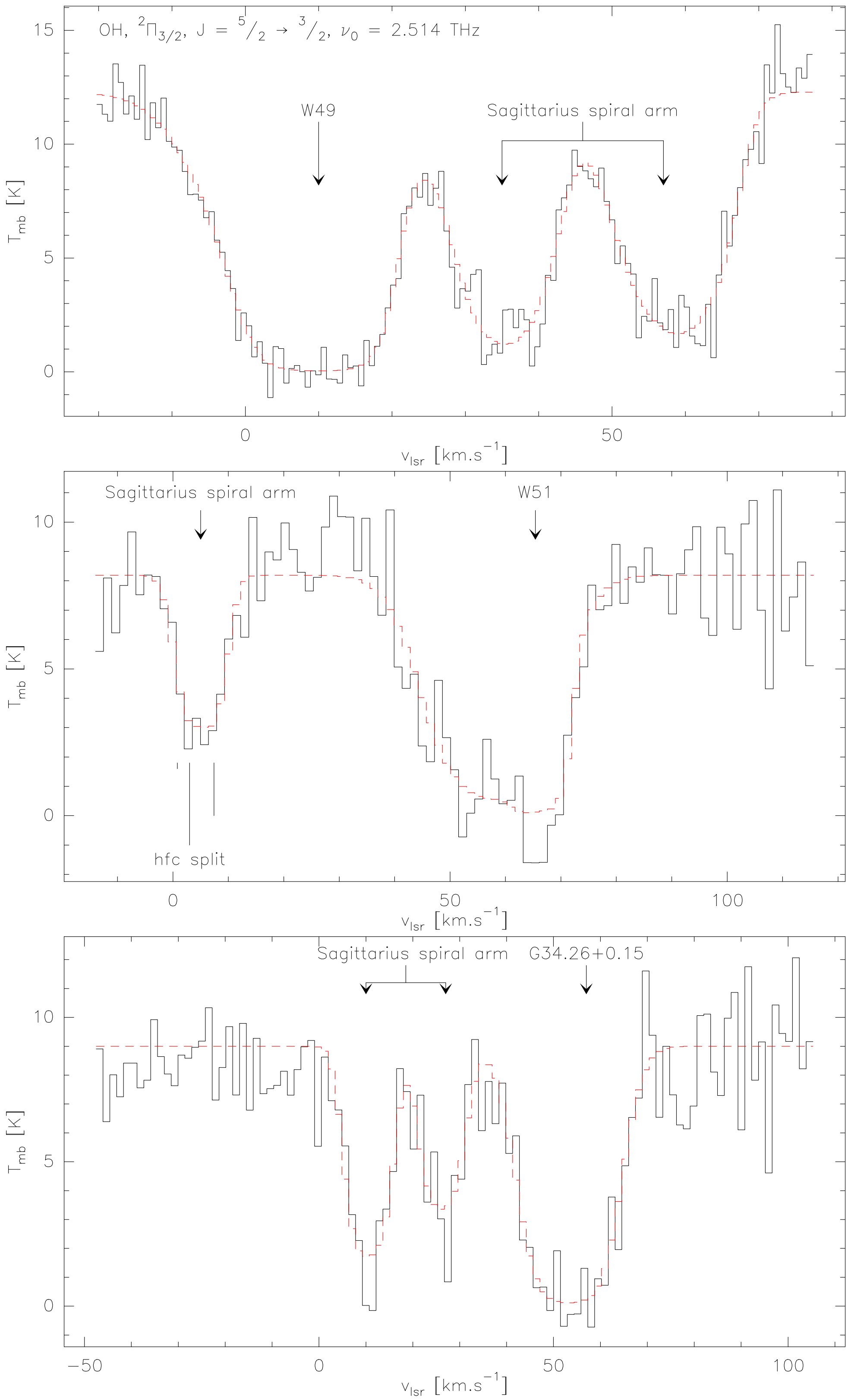

Fig. 11 OH observed in absorption against the dust continuum towards W49N (*top*), W51e4 (*middle*), and G34.26+0.15 (*bottom*). The velocities of the line-of-sight clouds are indicated on the x-axis. The relative positions and strengths of the hyperfine coupling splitting are indicated for the $v_{\rm lsr} = 7$ km s^{-1} component in the center panel. The data are in black, and the red dashed line is a least-squares fit. Reproduced by permission of Wiesemeyer et al. (2012).

5.4 GREAT Discovery of Interstellar Mercapto (SH)

The $^2\Pi_{3/2}$ $J = 5/2 \leftarrow 3/2$ Λ doublet of the mercapto radical (SH) near 1383 GHz, blocked by water absorption from the ground and not observable by *Herschel* HIFI, has been observed in the direction of the star forming region W49N by Neufeld et al. (2012) with GREAT on SOFIA. The spectrum (Fig. 10) reveals SH absorption both in material at the systemic velocity of W49N (and therefore local to it) and in a foreground interstellar cloud located along the sight-line. Supporting measurements of H_2S obtained earlier with the IRAM 30 m enabled Neufeld et al. to infer an SH/H_2S abundance ratio of $\sim$0.13, much smaller than predicted by standard models for the production of SH and H_2S by turbulent dissipation and in shocks. They concluded that an enhancement of the endothermic neutral-neutral reaction $SH + H_2 \rightarrow H_2S + H$ is implicated.

5.5 GREAT observations of warm OH absorption

The OH (hydroxyl) molecule was first detected in absorption in the interstellar medium (ISM) at 18 cm radio wavelengths by Weinreb et al. (1963). Although the hyperfine Λ doublet at 18 cm wavelengths has been well studied in both thermal and maser sources, this transition is dominated by relatively cool, diffuse gas ($N \sim 10^3\,\mathrm{cm}^{-3}$). GREAT is tuned to observe the far infrared Λ doubling and hyperfine structure lines of the OH $^2\Pi_{3/2}$ (119 μm; 2.514 THz) and OH $^2\Pi_{1/2}$ (163 μm; 1.8378 THz and 1.8377 THz) that probe denser, hotter gas than the 18 cm lines.

Wiesemeyer et al. (2012) have observed the OH ground state $^2\Pi_{3/2}$ $J = 5/2 \leftarrow 3/2$ (119 μm) line in absorption towards several ultra-compact HII regions with GREAT on SOFIA (see Fig. 11). These are the first velocity-resolved spectra ever observed of this transition. The line traces molecular gas in the spiral arm clouds along the line-of-sight and near the HII regions. Using *Herschel* observations of H_2O, they find that the H_2O to OH abundance ratio ranges from 0.3–1.

5.6 GREAT detection of OD absorption towards a low-mass protostar

Parise et al. (2012) report the detection of the OD ground state line at 1.39 THz (216 μm) in absorption toward the low mass protostar IRAS 16293-2422 (see Fig. 12). This is the first detection of OD outside the solar system. Using ancillary HDO absorption data obtained with the CHAMP$^+$ receiver at the Atacama Pathfinder Experiment telescope (APEX), they find an OD/HDO abundance of 17–90 where the absorption takes place. This is high compared with model values. Parise et al. suggest that dissociative recombination of H_2DO+ may result in the high observed abundance of OD with respect to HDO.

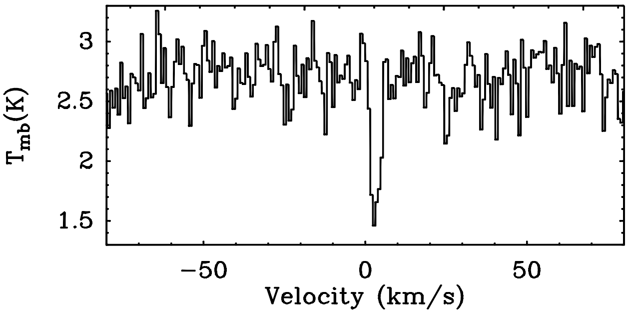

Fig. 12 GREAT OD absorption spectrum at 1.39 THz towards the low-mass protostar IRAS 16293 in Ophiuchus. Reproduced with permission of Parise et al. (2012).

5.7 HIPO and FDC observations of an occultation by Pluto

Stellar occultations probe dwarf planets like Pluto with a spatial resolution of a few kilometers and can be used to establish their diameters, reveal the presence of rings and moons, and detect and analyze the physical characteristics of their atmospheres. When a star passes almost directly behind the center of an occulting object that has an atmosphere, the atmosphere acts like a lens that produces a central brightening at mid-occultation. This brightening gives important information about the lower layers of the atmosphere (see French, McGhee & Sicardy 1998). Such a propitious alignment is rarely possible to view from ground-based observatories. On June 23, 2011, SOFIA demonstrated its unique capability to fly near the center of the shadow of an occultation by Pluto (see Fig. 13). About two hours before the occultation, a ground-based support team was able to call SOFIA by satellite phone with the information that the center of the shadow would cross 125 miles north of the position in the original flight plan. The flight path was then adjusted in mid-mission to put the aircraft on a path within about 100 km of the center of the shadow so that the critical central brightening could be observed by both HIPO and the German built Fast Diagnostic Camera (FDC), which is normally used as SOFIA's Focal Plane Imager (FPI). A paper has been submitted (Person et al. 2013).

5.8 HIPO/FLITECAM test observations of exo-planet transits

Community pressure for observing extrasolar planets with SOFIA is high. A first analysis shows that optical and near-infrared precision photometry and spectro-photometry of known transiting exo-planets with HIPO and and simultaneously with FLITECAM (a combination called FLIPO) is promising (e.g. Angerhausen et al. 2010), although difficult due to the need to control systematic noise (Becklin, priv. comm.). As a consequence, shared risk test observations of two transiting planets (HD 189733b and CoRoT-2b) were scheduled in early May 2013, but they fell victim to observatory development issues. These or similar transit events

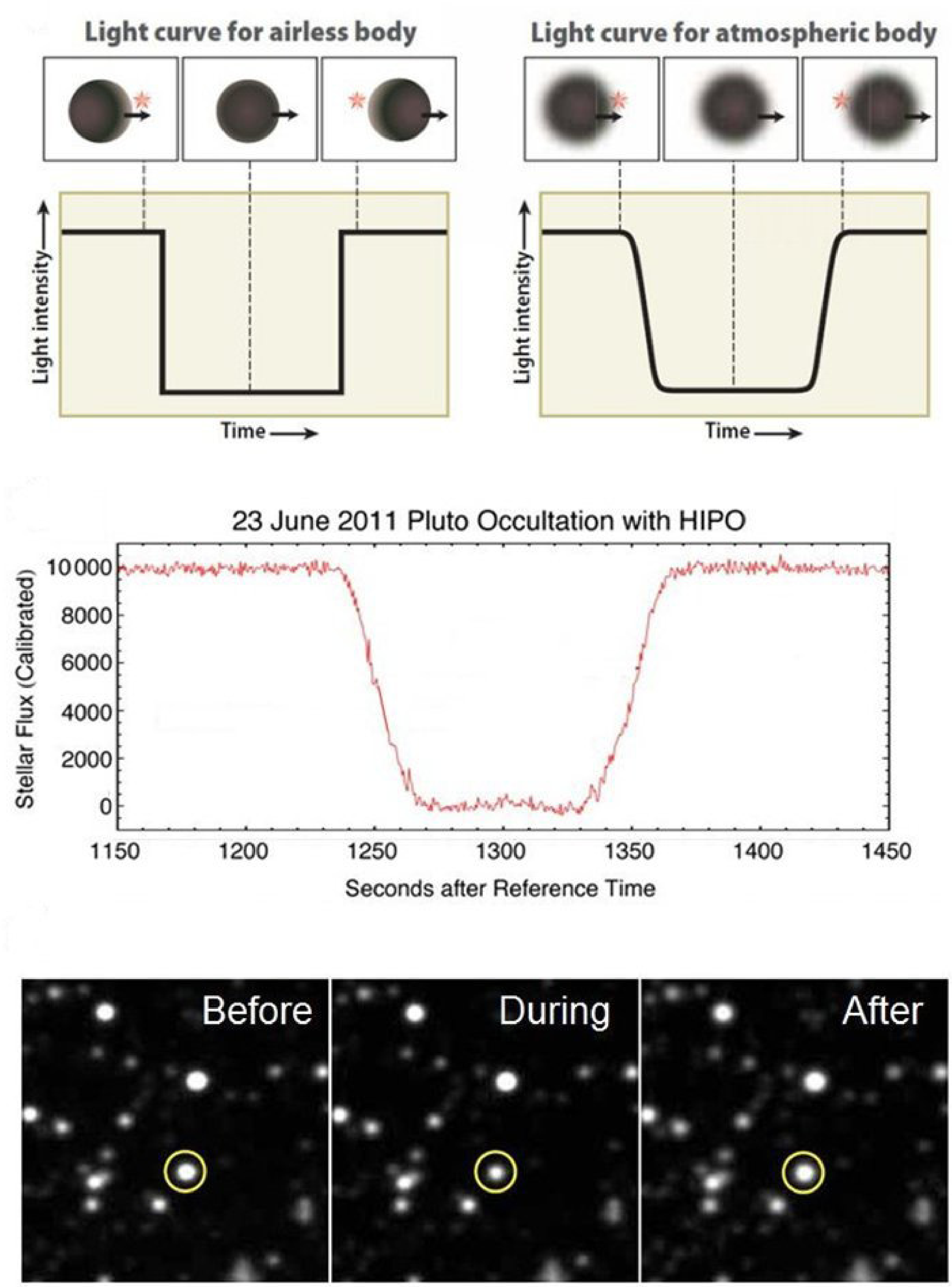

Fig. 13 Pluto occultation by a 14th magnitude star, showing that Pluto has an atmosphere (indicated by the slope of the ingress and egress of the occultation light curve). The slight central brightening is due to the focusing of light caused by Pluto's atmosphere and the slightly asymmetric position of the small brightening is interpreted as evidence for strong zonal winds. Figure courtesy of J. De Buizer (2012).

can be expected to be included in the forthcoming SOFIA Cycle 2 observing programme, but it is observatory policy that failed flights will not automatically be repeated and the corresponding observations must be reapplied for in the next call for proposals.

6 Future science potential of SOFIA (some examples)

Future science highlights and observational breakthroughs will mainly be enabled by SOFIA's new instrumentation, either not yet employed or not yet developed. The key in living up to its science potential is the future detector array technology and the corresponding multiplex advantage.

At the moment FORCAST has a 256×256 pixel mid-IR array, but GREAT is still currently observing with a single pixel (beam). EXES and FIFI-LS have not been flown and commissioned yet but will open up new science avenues, some of which will be discussed below.

SOFIA's unvignetted FOV is $8{\times}8$ arcmin, yet FORCAST is only using $3{\times}3$ arcmin. The question is what FORCAST could do if it had twice as large a detector array (i.e. $6{\times}6$ arcmin) thus quadrupling its FOV at a diffraction-limited angular resolution of about 3 arcsec at 30 microns. One idea comes to mind: large-scale monitoring of nearby starburst galaxies (e.g. M82) to detect deeply embedded, infrared-only, Type II supernovae! The question is whether this really needs SOFIA or whether it can be done from the ground with IR cameras at 10 and 20 microns. Perhaps a better reason for requesting FORCAST on SOFIA is broad-band imaging and grism spectroscopy as a follow-up of saturated ISO and *Spitzer* mid-IR observations. Recall that the spatial resolution of FORCAST at 24 microns is three times better than *Spitzer* and four times better than ISO. This will allow us to obtain a clearer picture of the hidden young stellar content of molecular clouds, i.e. large-scale mapping of regions of star formation. A larger FORCAST FOV will be useful for sky subtraction, as there will be parts on the array that are free of sources. The combination of mid-IR imaging with low-resolution 5–40 micron grism spectroscopy will help to identify the origin and life cycle of oxygen-rich vs. carbon-rich grains injected from various sources (e.g. AGB-stars vs. carbon-stars) and help characterize the grain composition (amorphous and crystalline silicates vs. graphite grains vs. poly-aromatic hydrocarbons) from their observed broad emission features in this wavelength range (see Draine 2003 and The Science Vision on SOFIA's website). In addition, the grain size distribution and grain growth in molecular clouds and protostellar environments can be studied from large-scale wavelength-dependent scattering observations. This type of observations would benefit from complementary polarimetric imaging observations with the new HAWC+ $60{\times}24$ pixel camera in the far-IR (50–250 microns).

As for GREAT, its follow-up development upGREAT with a $2{\times}7$ pixel heterodyne spectrometer array (dual polarization) will soon be available. Mapping the gas near massive stars in cooling lines (like [C II] and [N II]) will then be 14 times more efficient. With bigger arrays, we can afford to stare longer at a given position in the sky to increase the S/N of any detection. Also mapping larger areas will become possible, particularly the large-scale [C II] emission in nearby galaxies. A local example that comes to mind is the large molecular cloud associated with the NGC 3603 H II region and starburst cluster in the southern sky (Nürnberger et al. 2002) which encapsulates many aspects of photodissociation regions (Tielens & Hollenbach 1985a,b). UpGREAT will also operate at 2.5 and 2.7 THz, and ultimately 4.7 THz, which gives access to OH, HD, and ultimately [OI] observations, respectively. The ground rotational state of the OH molecule (an important molecule on the chemical pathway to water) has already been observed in absorption, with great success. Together with OD absorption maps (at 1.39 THz) of the same Galactic regions one can determine the true OD/OH abundance ratio of the respective molecules, as both these molecules are almost all in their ground rotational state. Then we can compare that ratio to the ratio of D/H in the interstellar medium and thus estimate the importance of deuterium fractionation (models of OD/OH predict an enhancement by a factor of 100 or more w.r.t. D/H). This has implication on the abundance of deuterated water.

Similarly one can determine the HD/H_2 abundance ratio. In molecular clouds, deuterated molecular hydrogen (HD) is the dominant reservoir of deuterium. HD at 112 micron has been observed with the ISO-LWS spectrograph in Orion in emission and towards W49 in absorption (Wright et al. 1999; Caux et al. 2002) and recently in the TW Hya debris disk in emission with the PACS spectrometer on *Herschel* (Bergin et al. 2013). Because HD is so rare, its emission or absorption can be assumed to be optically thin. H_2 column densities can be inferred from conversion of optically thin rare CO isotopic emission towards the same line of sight directions as the HD observations. Thus HD/H_2 should faithfully reflect D/H, which can be measured towards many sources throughout the Galaxy. Now, deuterium is only produced in primordial Big Bang nucleosynthesis and deviations from the cosmological ratio of $\mathrm{D/H} = 2{\times}10^{-5}$ must be due to astration, i.e. the destruction of deuterium in the course of stellar evolution over the lifetime of the Galaxy. Therefore, a measurement of the D/H ratio in dense gas based on the HD 112 micron (2.675 THz) line traces the Galactic star formation history (cf. SOFIA design reference mission http://www.sofia.usra.edu/Science/science_cases/guesten_v2.pdf).

One of the wilder ideas would be to map HD in emission over a whole warm giant molecular cloud ($T > 64$ K needed for rotational excitation to $J = 1$), many of which exist in the Galactic center circum-molecular zone (CMZ), as revealed by dust continuum observation with Bolocam at the CSO (Ginsburg et al. 2013). In this case, HD would be a proxy for the cold H_2, the primary constituent of molecular clouds. The homonuclear H_2 molecule would require a gas temperature of $T > 256$ K for exciting the quadrupolar $J = 2$ rotational level, much higher than required to excite HD, and hence unlikely to happen. Of course, there is the danger that the HD emission might be optically thick, thus not tracing the total mass of H_2 in the said CMZ molecular clouds. Indeed, given the huge amount of optical extinction ($A_V > 100$ mag) towards the CMZ, the local extinction at 112 micron may not be negligible and may cast some doubt on the possibility of a successful HD measurement. However, it would be worth trying.

It is also worth trying to detect HD emission from circumstellar gas disks around young stellar objects (Th. Henning, priv. comm.). Another interesting investigation that can be done with the high-resolution spectrometer GREAT is to measure the velocity profile of gas in [O I] fine structure line at 63 microns in young stellar objects (protostars) with disks and jets. HIFI on *Herschel* could not do such a study, as it could not observe at high frequencies beyond 1.9 THz. The PACs spectrometer could, but at low spectral resolution which is not enough to disentangle the emission from narrow-line disks (few km/s) from that of broad-line jets (few 10 $\mathrm{km\,s^{-1}}$). This a great niche for the GREAT high-resolution (H-channel) observations at 4.7 THz. If the line is seen to be narrow and comes from a protostellar gaseous disk, we may be able to derive the enclosed stellar mass from the rotation curve via Kepler's law, assuming we know from which disk radius the [O I] emission arises. In reality, the line will probably show both a narrow and broader component and discriminating them clearly may be tricky. Despite this being a pointed observation, a THz array is crucial to probe for extended emission from the shock-excited ambient gas that is hit and entrained by the jet (the beam-size of the [OI] line at 63 micron is about 6 arcsec (diffraction-limited); this angular resolution corresponds to a spatial resolution of about 0.1 pc at a source distance of 3 kpc).

So much for GREAT. What about good science with EXES? EXES is a slit spectrometer for the 5–28 micron wavelength region. In its high spectral resolution mode ($R = 120\,000$) it requires a slit width of about 1.6 arcsec, i.e. an excellent image quality that SOFIA is now approaching ($R = 85\,000$ is possible for a slit width of about 2.0 arcsec). EXES will make excellent use of the SOFIA Observatory. For example, it will do astrochemical studies of water in absorption and the gas phase chemistry of water in protostellar disks (5–7 microns). Clearly the distribution of water and ice during the entire star and planet formation process, and not just in disks, is a fundamental problem relevant to our own origins. EXES can provide a view of water that is complementary to *Herschel* (van Dishoeck 2012). EXES will be sensitive to the warmer, more abundant water that exists in close proximity to deeply embedded young stars. EXES will significantly improve on the lower spectral resolution of water vapor absorption studies carried out with ISO-SWS. Note that the spectral resolution offered by EXES is higher than the more sensitive MIRI instrument on JWST which is crucial to separate the lines.

SOFIA will also offer new observational insight on how much water is created in interstellar shocks. EXES, due to its high-spectral resolution, has the ability to spectrally resolve astronomical water emission lines, despite the presence of telluric water absorption lines in the remaining atmosphere below which SOFIA flies. Moreover, EXES has the ability to detect the primary gas constituent in molecular clouds, H_2. With the EXES instrument one can spectrally resolve the emission of molecular hydrogen in shocks, in the rotational transitions at 17.0, 12.3, and 9.7 microns, and provide a direct measurement of the total gas column density in the shock as a function of velocity. The $J = 2$–0 28.2 micron line lies right at the edge of the EXES detector cut-off and may or may not be seen. A dedicated 28 micron detector array (Si:In photoconductor) will be desirable to map molecular clouds in their primary constituent (see below). Only warm clouds are sufficiently excited, though, as the H_2 $J = 2$–0 excitation temperature is 512 K. The excitation temperature of the $J = 1$–0 HD line is 128 K, and colder clouds are more easily sampled mapping HD at 112 microns. Nonetheless, mapping the H_2 $J = 2$–0 quadrupole emission from warm molecular clouds (detected with *Spitzer* IRS by Ingalls et al. 2011) is a key goal in astrophysics. Because the H_2 line is weak, long integration times will be required, which is why 28 micron arrays with as many pixels as possible must be developed (1k$\times$1k or more; E. Young, priv. comm.).

FIFI-LS, like GREAT and EXES, will be one of the workhorses for SOFIA. At least this is what everyone expects. FIFI-LS is a far-IR integral field spectrometer, similar to the PACS spectrometer on *Herschel*. Its wavelength coverage is from 42 to 210 micron, its spectral resolution is 1000–3750, relevant to observe extragalactic targets. Indeed a prime target for FIFI-LS are starburst galaxies, such as the antennae pair of colliding galaxies (NGC 4038/4039). The collision region has been investigated with ISOCAM (Vigroux et al. 1996) and with the PACS spectrometer on *Herschel* (in the context of the *Herschel* key programme called SHINING, PI E. Sturm, MPE). The FOV of FIFI-LS (5$\times$5 pixels) in the blue (0.5 arcmin) and red channel (1.0 arcmin) is well suited to cover the collision region of these and other interacting galaxies. In particular, FIFI-LS is much more efficient in mapping speed than the PACS spectrometer which helps a lot when it comes to coverage of extragalactic regions of a few arcmin in extent. While PACS surely has already detected the most important ISM cooling lines like [O I] and [C II] in several major metal-rich starburst galaxies and also in many metal-poor starburst galaxies, extensive mapping still awaits the use of FIFI-LS. Large-scale [CII] mapping will be crucial to assess the prevalence of "CO dark H_2 gas" at the skin of molecular clouds where CO is destroyed but H_2 survives, particularly so in metal-poor dwarf galaxies with less dust and a harder interstellar radiation field (Madden et al. 2011, 2013). If unaccounted for, this introduces a strong bias to underestimate the total (molecular) gas mass in these galaxies.

Another FIFI-LS follow-up of PACS observations will be to confirm highly rotationally excited CO hot spots (eg. CO $J = 16$–15 at 162 micron), presumably the sites of new massive star formation (cf. Zinnecker & Yorke 2007), not only in interacting galaxies but also in dense gas in metal-poor starburst dwarf galaxies. Unique to FIFI-LS is the mapping shock-excited H_2O at 45 microns in these star forming galaxies. This will lead to new insights into the production rate of water in gaseous extragalactic environments depending on their metallicity. Notably, FIFI-LS can also serve as a spectroscopic pathfinder to identify wide-spread new complex large molecules, including pre-biotic polyaromatic hydrocarbons (PAH), predicted to show spectral signatures in the 100–200 micron range.

Finally HAWC+ and HAWC-pol. This combination of second generation instruments with 5 broadband and later 5 narrowband filters in the range 50–250 microns will be able to map the dust continuum emission and fine structure lines as well as magnetic field vectors of individual cold molecular clouds, some of which will be heated by internal star formation. HAWC+ will locate and characterize these sites of star formation, providing temperature and opacity maps, the luminosities of the powering sources, and the overall energy budget of the particular region. Indeed, like the PACS photometer on *Herschel*, HAWC+ covers the wavelength range that spans the peak of the far-infrared spectrum of star forming molecular clouds. However, while HAWC+ is similar to (but less sensitive than) the PACS photometer on *Herschel*, HAWC-pol has no equivalent on *Herschel*, as *Herschel* did not include a polarimetric instrument. HAWC-pol is unique to perform polarimetric imaging and delineate magnetic fields in molecular clouds before, during, and after star formation at angular resolutions of the order of 10 arcsec (Dowell et al. 2013). HAWC-pol may be useful to follow-up on low-angular resolution (5 arcmin) polarimetric images of star forming clouds obtained from PLANCK observations. Large-scale HAWC-pol mapping will also provide statistical estimates of magnetic field strength (Chandrasekhar-Fermi method). HAWC+ and HAWC-pol are scheduled to be commissioned in 2015.

Looking further into the future, we expect NASA to call for third generation instrumentation. One would guess that the proposals that will be submitted may include a 30–60 micron high-resolution spectrometer (SOFIA has a spectroscopic gap in this wavelength interval); also a dedicated very high-resolution R $\sim 10^5$ array spectrometer, perhaps a tunable Fabry Perot system, to measure the 28 micron $J = 0$–2 rotational ground-state absorption in a number of molecular hydrogen clouds against strong background dust continuum sources (e.g. SgrB2), thus allowing us to determine their H_2 column densities and their gas masses. These are fascinating prospects presenting us with formidable but not insurmountable technological challenges. We can do it, if the funding can be found, either in the US or in Germany, or possibly from new international partners.

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A Appendix

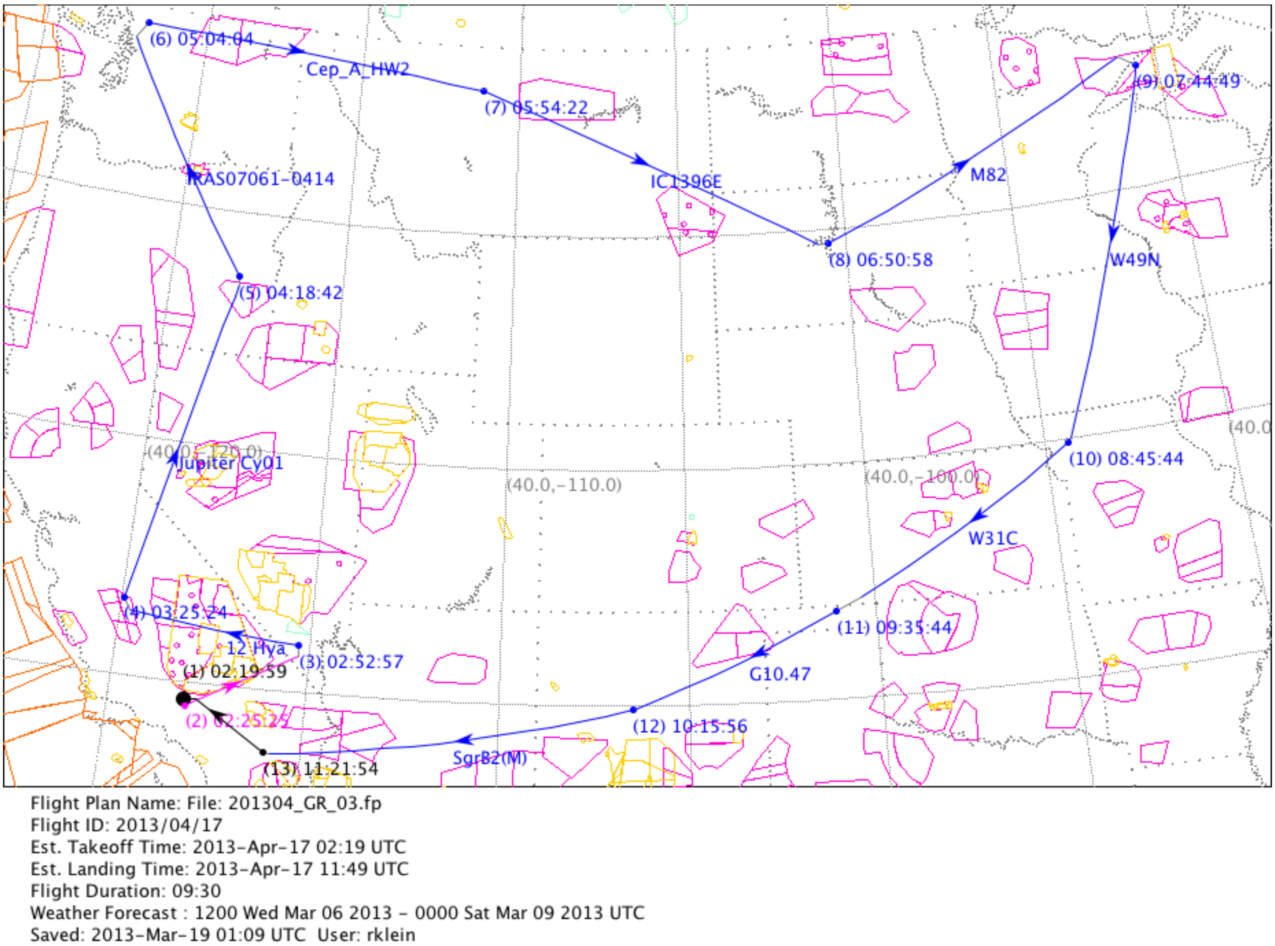

Fig. A1 Example of a GREAT flight plan over the continental United States, with takeoff and landing in Palmdale, California. Notice the names of the astronomical targets observed along the various flight legs. Flight plan courtesy of R. Klein.