Radiative and mechanical feedback in regions of massive star formation

Short name: FEEDBACK
Co-PI's: Alexander Tielens & Nicola Schneider

Scientific Context

Context: Massive stars stir up the ISM through their stellar winds, ionization & heating, radiation pressure, and supernova explosions. In addition, they photo-dissociate molecules and heat neutral atomic and CO-dark molecular gas through the photo-electric effect on large molecules and small dust grains. This mechanical and radiative feedback of massive stars on their environment regulates the physical conditions, sets the emission characteristics, influences the star formation activity through negative (molecular cloud dissolution) and positive (cloud compression) feedback processes, and drive the evolution of the ISM of galaxies. ***Understanding the physical processes that regulate the feedback of massive stars on their environment is a key question within modern astrophysics and a major theme of SOFIA's science***.

Aims: We propose to use the [CII] 1.9 THz (157µm) line to study the interaction of massive stars with their environment in a sample of sources that span a range in stellar characteristics from single OB stars, to small groups of O stars, to rich young stellar clusters, to mini starbursts. The aim of these observations is to quantify the mechanical energy injection and radiative heating efficiency in regions dominated by these different processes (stellar winds, thermal expansion, radiation pressure).

Method: The proposed Legacy Program is developed to take full advantage of the unique capabilities of the upGREAT/SOFIA combination: The high spatial (14") and spectral (sub-km/s) resolution of the 14 element LFA upGREAT heterodyne spectrometer coupled with the nimble telescope of SOFIA allows for efficient mapping of the [CII] line over large (100's to 1000's of square arcmin) areas.

Anticipated results: The [CII] line uniquely provides the kinematics of the gas exposed to the mechanical energy input by massive stars and therefore directly measures the mechanical energy injection into the medium. In addition, for low to moderate densities and UV fields, this line is the dominant cooling line of the gas, and observations then directly yield the radiative energy injection/heating efficiency of the gas. Thus, by surveying regions with a range of massive star formation activity, we will quantify the relationship between star formation activity and energy injection and the negative and positive feedback processes involved, and link that to other measures of activity on scales of individual massive stars, of small stellar groups, and of star clusters. These [CII] maps, together with the less explored [OI] 63µm line (observed in parallel), provide an outstanding data base for the community and will serve as a starting point for many studies and follow-up observations.

Synergies: ALMA studies of the red-shifted [CII] line are widely used as a star formation rate indicator in the far Universe but the relationship to local physical processes is poorly understood. Likewise, stellar feedback is a key ingredient in ΛCDM cosmological simulations. The proposed program will provide a ground truth for these types of studies and will leave a high and long lasting impact on the field of high mass star formation and its feedback from local to cosmic scales.

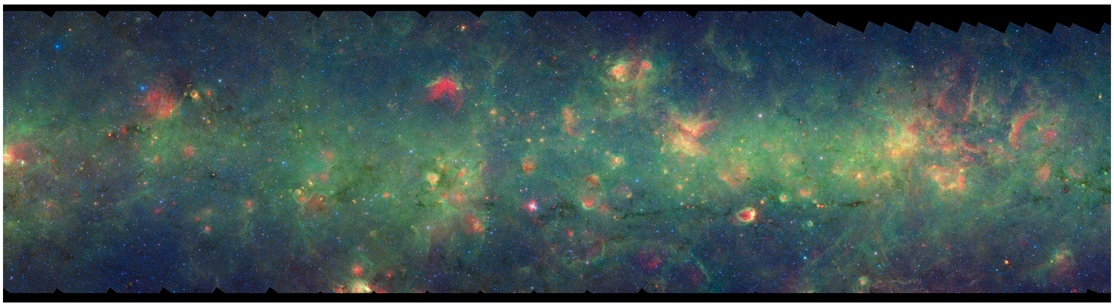

Figure 1: Composite image of the galactic plane revealing the bubbly nature of the ISM of the Milky Way obtained by the GLIMPSE Spitzer Legacy Program (Churchwell et al 2006). Blue: IRAC 3.6μm tracing stars; Red: IRAC 8μm is PAH emission tracing PDR surfaces of bubbles; Red: 24μm tracing warm dust in bubble interiors.

Scientific Justification

1. Introduction and background

Interaction of massive stars with their environment regulates the evolution of star forming galaxies. Mechanical and radiative energy input by massive stars stir up and heat the gas, producing cloud & intercloud phases of the interstellar medium (ISM), disrupt molecular clouds halting star formation, but also simultaneously compress surrounding gas, potentially triggering new star formation (Kim & Ostriker 2013). Stars control the radiative energy budget of the ISM and its emission characteristics. Photons from massive stars with energies >13.6 eV ionize hydrogen, creating HII regions. Less energetic photons couple to the gas through photo-electrons from large molecules that heat gas in PhotoDissociation regions (PDRs) surrounding HII regions and on a much larger scale in the diffuse ISM (Hollenbach and Tielens 1999). Through their winds and explosions, stars also stir up the ISM dynamically, driving turbulence and sweeping up gas into large bubbles. This injection of mechanical energy into the ISM is the origin of the Hot Intercloud Medium and a source of turbulent pressure that supports the gas disk and the clouds therein against galactic- and self-gravity (McKee and Ostriker 1977). Cosmological simulations show that stellar feedback controls galaxy evolution (Ceverino & Klypin 2009). These processes act on much smaller scales than cosmological simulations can resolve and they are included in somewhat ad-hoc sub-grid physical prescriptions. Feedback from massive stars is also generally believed to play a critical role in driving galactic super-winds that enrich the InterGalactic Medium, control the galaxy mass function, mass-metallicity relation, and other global galaxy characteristics (Hopkins et al 2012). Yet, from an observational point, our understanding of stellar feedback on the micro-scale, that is at the basis of these models, is very limited.

The mid-IR Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) has revealed that bubbles are important morphological features in the ISM of the Milky Way (Churchwell et al 2006; Fig.1). In general, these bubbles trace the effects of feedback by massive stars on their environment. They may be caused by the thermal expansion of HII regions driven by the overpressure of ionized gas, by the mechanical action of stellar winds from massive stars creating X-ray emitting hot gas, and by the effects of radiation pressure on surrounding dust and gas (Spitzer 1968; Weaver et al. 1977; Draine 2011; Haid et al 2016). This interaction can lead to a shredding of the nascent molecular cloud, halting star formation. Massive stars can also provide positive feedback to star formation as gravity can more easily overwhelm cloud-supporting forces in swept-up compressed shells (Elmegreen and Lada 1977). The GLIMPSE survey provides clear examples of positive feedback events that are very amenable for further studies in the processes that drive triggered star formation (e.g., RCW 120; Zavagno et al 2010; Deharveng et al 2010). Far-infrared imaging surveys by *Herschel* revealed the importance of filaments for molecular cloud- and star-formation processes (e.g. Andre et al 2014, Schneider et al 2012). Mostly unexplored is how radiation and stellar wind impact on these filaments and how that influences subsequent filament/cloud evolution and star formation. Detailed studies of these bubbles and filaments allow us to probe the underlying physical processes, the structure and physical properties of the ambient ISM into which they are expanding, the hydrodynamical response of gas and dust in the ISM to stellar action, and the radiative coupling of gas and dust to the intense photon fields of massive stars. However, the modest velocities and large scale sizes of these regions have hampered in depth studies of the evolution of bubbles driven by massive stars

The [CII] 157 μm line offers a unique probe of the radiative and kinetic interaction of massive stars with their environment. The C^+ ion is the dominant form of carbon in HI and CO-dark molecular gas layers and, on a pc-sized scale, the [CII] line is the dominant cooling line of PDR surfaces of FUV illuminated molecular clouds where stellar photons dissociate molecular gas and heat it to temperatures of ~200K. The 14 pixel upGREAT heterodyne high-spectral resolution spectrometer can efficiently probe over large scale sizes (hundreds to thousands of squared arcminutes) and at high spatial (14") and spectral (sub-km/s) resolution the dynamical interaction of massive stars with their environment through HII region expansion, radiation pressure, and stellar winds. In this way, upGREAT can probe how massive stars interact dynamically with their natal clouds and control star formation through e.g., shredding of these clouds, injection of turbulence into these clouds, as well as triggering of new star formation.

2. Goals and source selection

This SOFIA Legacy Program will take full advantage of the rapid mapping speed and high spectral resolution of the upGREAT 14 element heterodyne array to survey a broad sample of regions of massive star formation in the [CII] 1.9 THz line to measure the dynamic and radiative response of interstellar gas to massive stars.

The objectives are:

1) To quantify the kinetic energy input into the ISM by massive stars as a function of star formation activity (cluster size, spectral type, stellar wind) and evolutionary stage of the region both in terms of the generation of large scale motions as well as the local injection of turbulence into molecular clouds.
2) To quantify the radiative coupling of interstellar gas to the FUV photons of massive stars and determine the heating efficiency of neutral atomic and CO-dark gas.

In parallel, the 4.7 THz channel of upGREAT will give a – though undersampled – complete map of the regions observed in the [OI] 63μm line, which will provide the community with unique complementary data in the context of PDR and shock modeling.

We have selected a sample of sources (see below 'Description of sample') from the *Spitzer*/GLIMPSE and the *Herschel* HOBYS, Gould Belt & HiGal Legacy/Key Programs. In the selection we ensured that a wide range in star formation activity is covered from regions dominated by single O stars, by small groups of O stars, by compact clusters, by super star clusters, and by mini starbursts. In addition, we have included regions at different stages of their evolution. Morphology was an important criterion and we incorporated HII regions that are (almost) perfect spherical bubbles, bipolar structures or show a more complex structure with fragmented shells, pillars, and globules. Finally, regions with dispersed star formation activity and filaments, possibly formed by colliding flows were considered. Furthermore, the selected sources include regions dominated by the thermal expansion of ionized gas (Spitzer-type expansion), by stellar wind driven flows, by radiation pressure, by the concerted interaction of multiple expanding HII regions, by the presence of nearby rich OB associations, and by the action of converging flows associated with the large scale spiral arm structure of the Milky Way. This will allow us to study feedback on a wide range of scales both in size (from sub-pc to tens of pc) and energy (energy of a single O star to that of clusters of stars containing tens to hundreds of OB stars). All of these interactions are key to the evolution of the ISM of galaxies. Hence, this *SOFIA* Legacy Program will impact directly our understanding of the role of feedback in the local arena and the proposed program will create a physical, observational, and modeling framework that will be key to interpret studies of more distant galaxies over cosmic time and guide theoretical simulations of galaxy evolution.

The sample includes "poster child" sources dominated by these different dynamical processes (thermal, wind, radiation pressure) and covers the parameter space of star formation activities and evolutionary stages. Much ancillary data is available for all regions as they have been studied in depth in a variety of *Herschel* Key and *Spitzer* Legacy programs and our team consists of experts (PIs and co-Is) of these programs. Specifically, these surveys provide detailed spectral energy distributions, luminosities, dust temperatures, and column densities at spatial scales that are comparable to those that

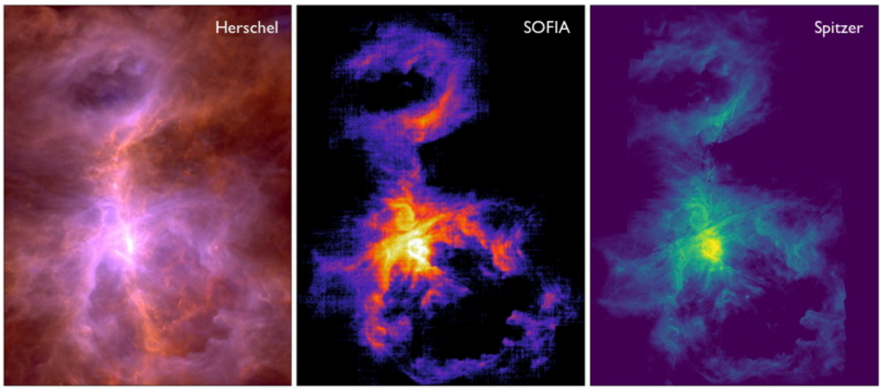

Figure 2: Left: The far-IR (PACs 70 (blue) & 160µm (green)) and sub-mm (SPIRE 250µm (red)) emission of the Orion molecular cloud, measuring conversion of FUV radiation from massive stars to dust emission in PDRs. Center: The integrated [CII] 1.9 THz (157µm) emission (upGREAT), tracing cooling and kinematics of PDR and CO-dark gas. Right: 8µm PAH emission (IRAC) outlining FUV illuminated PDR surfaces. This comparison does not do full justice to the richness of the [CII] data as there are ~2,000,000 spectra allow a detailed study of the gas kinematics (Pabst et al 2018).

will be obtained by upGREAT. All data sets are already at our disposal. In addition, CO has been used to map the molecular clouds while Spitzer/IRAC studies have outlined the PDR surfaces that are exposed to FUV photons from massive stars. Optical, IR, and radio studies have determined stellar spectral type and ionized gas properties.

3. Preparatory work and objectives of the current proposal

Figure 2 summarizes the results of the square degree survey of the Orion Molecular cloud centered on the Trapezium cluster in the [CII] 157µm line with upGREAT on SOFIA (Higgins et al 2018) and compares this [CII] map with *Spitzer*/IRAC and *Herschel* data. Each map clearly shows the direct interaction of the Trapezium cluster with the dense molecular core (center), the large, wind-blown bubble, associated with the Orion Veil (South), and the bubble created by the B stars illuminating the reflection nebulae, NGC 1973, 1975, and 1977 (North). The high spectral resolution (~0.2 km/s) is unique in that it allows, for the first time, a detailed investigation of the kinematics of the gas and, using position-velocity diagrams, 5 coherent velocity structures have been identified in this map characteristic for expanding shells. The prominent one towards the South is associated with the Veil bubble blown by the stellar wind from θ^1 Ori C (Pabst et al 2018; Fig 3). The observed velocity structure is well fitted by a half-shell expanding at 13 km/s towards us into the low density foreground materials while expansion towards the rear is inhibited by the dense molecular core behind the Trapezium. The presence of this wind-blown bubble was known from X-ray observations of the hot gas (Guedel et al 2008) and the shell of swept up material is also discernible in dust and PAH emission. However, only the [CII] emission can quantify the kinetics of this shell and the energy involved. While theoretical studies generally focus on photo-ionized & -evaporative flows (Williams & McKee 1997), these data reveal that stellar winds are far more effective in destroying molecular cloud cores and stopping star formation. Theoretical analysis of the wind bubble (Weaver et al 1977) implies that the bubble has been expanding for some 200,000 years and almost all of the stellar wind energy has gone into sweeping up the surrounding molecular gas (Pabst et al 2018). **Mechanical feedback by massive stars drives the evolution of galaxies. The proposed observations will allow us to quantify the kinetic energy input by different interaction processes (thermal expansion, winds, radiation pressure) and on scales from single stars, to small groups, to large clusters.** The cavity "evacuated" by the hot gas allows stellar FUV photons to travel some 2pc unimpeded and illuminate the inner surface of the bubble. The gas heated by the FUV cools through the [CII] line and, focusing here on the extended [CII] emission where this line dominates the gas cooling, the observed luminosity (200 $L_\odot$) corresponds to a heating efficiency of some 0.6%. So, the combination of the mechanical and radiative interaction creates the large scale [CII] emission from this region of massive star formation. As the [CII] 1.9 THz line is the dominant cooling line of the gas, these observations can be directly converted into the heating efficiency (Fig. 4; see Pabst et al 2017 for details). Theoretically, the heating efficiency depends on the ionization parameter, $\gamma=G_0T^{1/2}/n_e$ with G_0 the

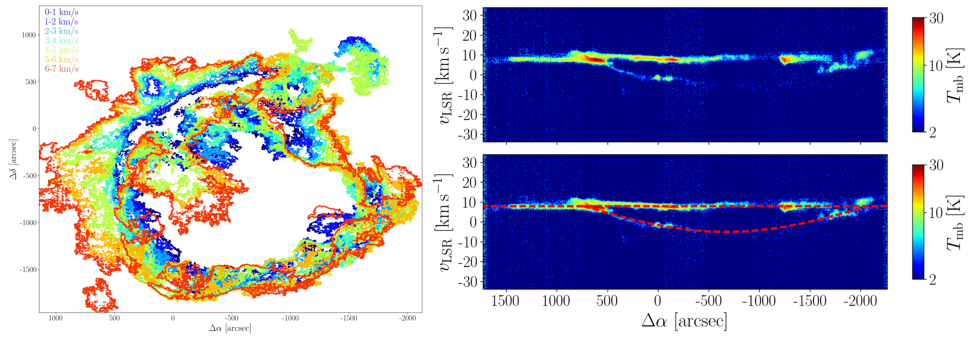

Figure 3: Left: Outlines of the Veil shell in 1km/s wide channels (Blue to red corresponds to 0 to 7 km/s). With increasing v_{LSR}, the filament is displaced outward, away from the bubble center, revealing the kinematic signature of an expanding half shell (Pabst et al 2018). Right: An example of a position-velocity diagram of the [CII] emission. The bright emission originates in the PDR surface of the high density, background molecular cloud. The fainter arced emission traces the emission of a half sphere expanding at constant velocity into the lower density foreground gas, the Veil. The dashed red line shows a fit to this data.

intensity of the radiation field in terms of the average interstellar radiation field, T the gas temperature and n_e the electron density (Bakes and Tielens 1994). In a stronger radiation field, PAHs and very small grains charge up and the heating efficiency drops. An increased electron density decreases the charge of these species and will tend to increase the heating efficiency. While the data show a similar trend with ionization parameter, theory seems to over-predict the heating efficiency. Moreover, the data show a large spread in heating efficiency at any given ionization parameter. These variations are related to the spatial location in the region, indicating a dependence on local conditions not caught by the ionization parameter or on the history of the region. **The coupling of FUV photons to the gas is a key process that sets the structure and physical conditions in PDRs and their emission characteristics (Hollenbach and Tielens 1999) as well as regulates the phase structure of the ISM (Wolfire et al 1995; 2003). The proposed observations will sample a wide range of physical conditions including G_0, n_e, T and spectral type of the illuminating star and are thus well suited to quantify the radiative heating of interstellar gas in different environments.**

The proposed Legacy Program will provide a rich treasure trove of data that can be used for a multitude of projects by the community. Each of the selected sources is a poster child of its class and has been studied in depth at other wavelengths, including molecular lines such as CO, HCN, CS, near-IR spectroscopy for spectral typing & the star formation characteristics, optical observations of YSO jet and outflow activity, Hα and other optical line studies of the ionized gas properties, etc. Anticipated community follow up project include:

1) In depth studies of the structure and characteristics of photodissociation regions. The [CII] line is an important coolant of warm neutral atomic and CO-dark molecular gas in PDRs. The selected sample spans a wide range in physical conditions that are well probed by [CII]. In addition, the (undersampled) [OI] 63μm maps – obtained in parallel with [CII] –will be bright in the densest regions illuminated by strong FUV fields and will provide a firm basis for follow up studies with either upGREAT or HIRMES. Since the [OI] line is potentially a tracer for shocks, we will compare our data to the results of dedicated shock modeling. Altogether, these studies can address issues such as the relative importance of the [CII] and [OI] for gas cooling in regions of different physical conditions, the role of self absorption in [OI] and [CII] emission and its effect on the analysis of low resolution, Galactic and extragalactic observations, and the origin of the [CII] deficit in (Ultra)Luminous IR Galaxies.

2) Within the field of star formation, the observations can form the basis for a study on the dynamical response of newly formed stellar clusters to the disruption of their nascent clouds. Many of the regions selected show evidence for triggered star formation in their dense, swept up shells and the [CII] observations, combined with molecular observations, can provide physical conditions and pressures in these regions. Furthermore, radiative feedback will impact dust temperatures within the molecular cloud, modifying the initial conditions for collapse and affecting the evolutionary criteria of protostars.

3) Massive stars have a profound influence on the structure of the ISM and the proposed observations

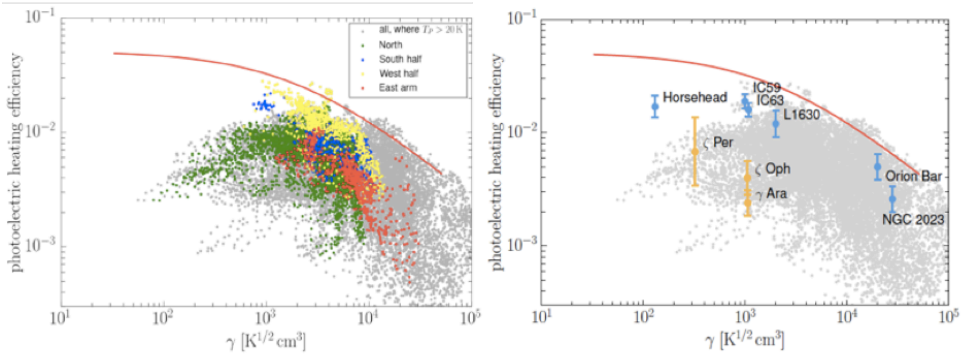

Figure 4: Cooling efficiency as derived from the observed [CII] cooling line and the far IR continuum as a function of the ionization parameter, $\gamma = G_0\, T^{1.2}/n_e$, which regulates the ionization stages of PAHs and hence the photo-electric heating efficiency. Right: Existing observations of a few well-studied PDRs and diffuse clouds (Pabst et al 2017). The red curve is a theoretical prediction (Bakes and Tielens 1994). Grey points are the multitude of data that are probed in the Orion survey (Pabst et al 2018). Left: The different colors identify individual regions of the Orion map. Part of the unexpected, large spread in heating efficiency is linked to specific interaction zones in the Orion area.

can address such key questions as: Are dense filaments formed due to the interaction of expanding, compressed shells around HII regions? What is the role of mechanical and radiative feedback in the formation of e.g., pillars? We note here that NGC6334 and RCW36 provide prime examples of the former while M16 and NGC 7538 are clear cases of the latter.
4) The contribution of molecular cloud surfaces and dense, bright PDR gas associated with massive stars to <u>the global [CII] 157 μm emission from star forming galaxies</u>. This line is, generally, the brightest emission line in the far-IR spectra of star forming galaxies and, with ALMA, is now commonly used at high redshifts to infer star formation rates. Yet, the origin of this line in local galaxies is unclear as neutral atomic clouds, dense and bright PDRs, low density ionized gas, and surfaces may all contribute to the global [CII] emission.
5) Filaments play an important role in <u>molecular cloud- and star-formation processes</u> (e.g. Andre et al 2010, Schneider et al 2012). The OI 63 μm line is predicted as a tracer for the fast formation of dense filaments because the expected low-velocity shocks in this scenario should cool by this FIR line. The CII 157 μm line will trace these filaments when the formation time scale is long and mostly governed by chemistry. As our sample includes prominent filamentary clouds, analysis of this data will lead to better understand the coupling of turbulence with heating and cooling processes that drive star formation as well as structural changes in the ISM. While the [OI] maps will be undersampled, they will serve as a starting point for follow up studies by the community.

<u>Description of sample</u>: The source selection is based on star formation activity, morphology, driving mechanism of the expansion, and evolutionary stage. The full sample allows us to study systematically the effects of or factors involved in: the cluster size (Orion, RCW49), stellar wind activity (e.g., O stars lose 0.1-1 $M_{\odot}$; WR stars have lost ~10's of $M_{\odot}$), FUV photon leakage from compact HII regions (M16, NGC 7538, diamond ring in Cyg X), evolutionary stage (expansion time evolves along the sequence Orion, M17, NGC 7538, diamond ring in Cyg X), sculpting of pillars, spires, & bright rim clouds (M16, NGC 7538), driving mechanism [thermal expansion, stellar wind, radiation pressure: RCW 120, RCW 49, RCW 79)], effect of environment [isolated O stars (RCW120), converging flows due to nearby OB association (Cyg X), mini starburst activity (NGC 6334), starburst activity fueled by the converging flows where spiral arm meets the central bar (W43), compact versus dispersed star formation (RCW 49, NGC 6334), small versus large scale filamentary structure (W40, RCW36, NGC 6334, Cyg X)]. While one goal of this program is to understand the individual factors involved in the feedback of massive stars on their environment, we specifically include three large, complex regions (NGC 6334, W43, Cyg X) as the concerted action of multiple, nearly simultaneous regions of massive star formation in close proximity will be key to understanding observations of massive star forming complexes in external galaxies.

Technical justification, observing strategy, and analysis method

Feasibility: upGREAT's unique capabilities for large scale on-the-fly mapping of bright [CII] emission from regions of massive star formation are well demonstrated by the studies of L1630, the OMC, and 30 Dor. The proposed fully sampled [CII] surveys will reach a similar limited line flux as those surveys (5σ detections of [CII] surface brightness of 2.5 10^{-5} erg/cm^2/s/sr). In parallel mode, we will observe the [OI] 63μm transition but in the [CII] observation will be the main driver for our observing strategy. We have estimated the [CII] 157μm surface brightness from 8μm PAH emission maps (convolved to the upGREAT beam; Fig 5) because the latter are signposts of bright PDR gas and [CII] and 8μm brightness are very well correlated with each other (Pabst et al., 2017, 2018). The map extent was defined by a certain expected low level [CII] integrated line intensity (varying between 100 and 250 K km/s, depending on source) and compared to maps of the far-UV field, derived from 70 and 160μm Herschel/PACS flux maps. Typically, the mapping area starts above 100 G_0.

Observing strategy: Using the GREAT online time estimator with the average T_{sys} from the Orion survey (2500K) returns a sensitivity over a 1 km/s bin of a 1σ noise rms of 0.7K (T_R*) in an individual pixel in an ON-target time of 2.4s. The sources have a range of velocities from -55 to 100 km/s and atmospheric absorption does not change significantly for [CII] over this velocity range. The [OI] is affected more by telluric transmission, but we expect to reach a 1σ noise between 0.65 and 0.8K (T_R*), depending on velocity. We will follow the successful observing strategy developed for the Orion A survey and employ the total power array OTF mapping mode which makes use of the array geometry to quickly map large regions. We will break each region into square tiles with an edge length 435 arcseconds (6*72.6 arcseconds). In order to reach our noise goals, each tile is observed 4 times, twice each in the X and Y directions. Using upGREAT's image rotator it is possible to flip the array so each position on the sky is covered with 8 independent pixels. This will greatly reduce performance differences between pixels and will result in a smoother noise distribution. We propose to observe with an OTF spacing of 5.2 arcseconds with an integration time of 0.3s, resulting in a total of 84 OTF dump per scan line. The total time for an OTF scan is then 25.2s. This is, together with the OFF observation (see below), within the recommended Allan stability time of between 30– 35s. Based on our experience with Orion A, we are confident this setup will return excellent data quality. This setup returns a total integration time per pixel (5.2 arsceconds) of 2.4s. Each tile (52 square arcmin) will take ~50 minutes to complete (twice in X direction and Y direction), including overheads. A slight shift between the two X- and Y-coverages, implying no overhead for the [CII] observations, will ensure that the [OI] maps observed in parallel will be regularly, although not fully Nyquist, sampled. After each OTF scan line, a reference measurement will be taken. Care will have to be taken to identify emission free off positions. For regions of very extended emission, a local reference position will be identified for each set of tiles, which will be calibrated against an emission free position further out. This procedure was demonstrated successful in the Orion A project. Initial, emission free regions will be identified by examining 8μm IRAC and 70μm PACS maps. For each source, we request an additional 30 minutes to confirm and validate these off positions. With a typical leg length of ~3hrs, we can expect to do up to 3 tiles (~150 square arcmin) per flight. All sources will require multiple flights and we will validate the performance of the instrument by observing the same bright region on each flight, ensuring ease of cross calibration. The sources (Table 1) are well distributed over the Northern and Southern sky and the observing time required can easily be distributed over a few flights. Hence, we do not foresee strong constraints on flight planning.

Data reduction: Maps will be reduced using the calibrated data from the upGREAT pipeline in Class. Based on our experience from other mapping projects we have developed an advanced set of tools to remove instrumental effects such as instrument baseline distortions (using a spline base approach) and off contamination (Higgins et al. 2018). For each individual source, level 3 products with calibrated [CII] maps will be delivered to the SOFIA Science Center by the GREAT team within 60 workdays after the end of the flight series in which its map is completed. For science analysis, further issues such as e.g., standing waves still need to be addressed and individual tiles within the maps have to be carefully stitched together. We will deliver level 4 products in which these issues have been resolved 3 months after level 3 products have been delivered. The undersampled [OI] data, observed in parallel, will also be provided to the SOFIA Science Center as a level 4 product.

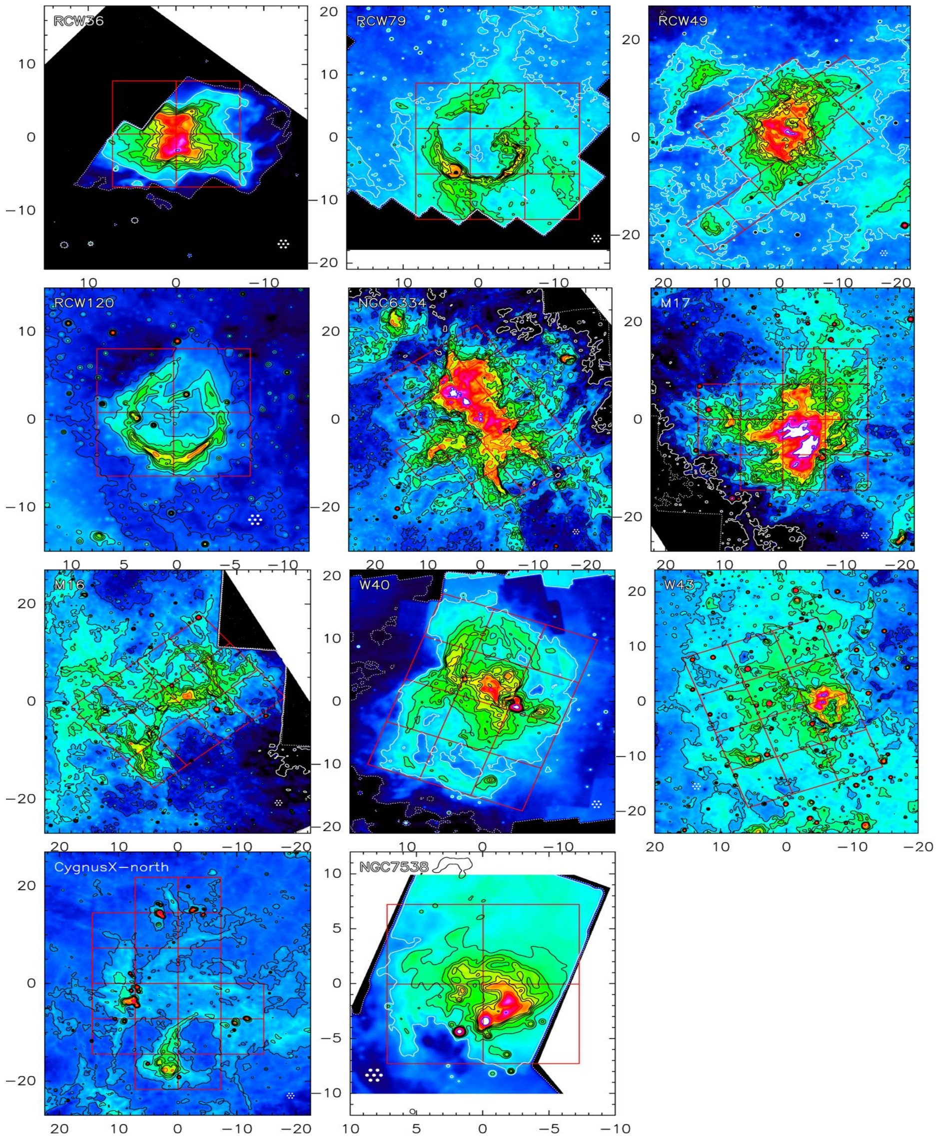

Figure 5: IRAC 8µm map (color) of the sources in the sample tracing the PDRs in these regions convolved to the upGREAT beam. Contours are predicted [CII] 1.9 THz integrated line intensity based upon the [CII]-8 µm relation derived for L1630, Orion, and 30 Dor. Contour levels are: white dashed (50 K km/s), white (100 K km/s), black (150(50)400 K km/s), red (500 K km/s), blue (1000 K km/s). Box units are in arcmin. The upGREAT 7 beam pattern is plotted in a corner in each box, illustrating that much finer detail than visible in these images can be traced. The overlaid red boxes represent the tiles that we propose to observe for each source .

Table 1: Source list: Visible from Palmdale/New Zealand/both locations. The center positions of two sources (NGC6334, NGC7538) are included in the ROC list but proprietary is waived.

Source	RA(2000)	Dec(2000)	d	V_{lsr}	SF activity	Morphology	Area	t[a]
	[h m s]	[o ' "]	kpc	km/s	SpT & cluster		arcmin	h (#tiles)
RCW36	08 59 00	-43 48 49	0.7	5	O8, B-cluster	bipolar	15x15	3.1 (4)
RCW79	13 40 18	-61 44 12	4.3	-50	2 O4, 10 late O	venting, evolved bubble	20x20	7.0 (9)
RCW49	17 12 18	-38 27 43	4.2	0	2WR, 12 early O, compact cluster	Strong stellar winds; fragmented bubble	20x30	9.35 (12)
RCW120	17 12 18	-38 27 43	1.3	-10	1 O7	thermal bubble	15x15	3.1 (4)
NGC6334	17 19 03	-35 48 56	1.35	-5	mini starburst	dispersed interacting HII regions	20x35	12.5 (16)
M17	18 18 31	-16 34 52	1.9	22	2 O4 10 late O	prominent (X-ray) evolved stellar wind region	20x30	10.1 (13)
M16	18 18 56	-13 48 26	2.0	25	O4, 10 late O	radiation sculpted interfaces; pillars of creation	20x30	9.35 (12)
W40	18 30 15	-02 44 31	0.26	5	1 O, 2 B	bipolar filament	20x30	9.35 (12)
W43	18 46 54	-02 14 11	5.5	100	mini starburst	converging flow spiral arm/bar	20x30	9.35 (12)
Cygnus X	20 37 59	41 45 09	1.4	-3	Nearby Cygnus OB 2: 3 WR,~50 O	converging flow filaments; evolved bubble; compact HII regions	20x35	14.0 (18)
NGC7538	23 13 40	61 30 00	2.8	-55	O3	evolved bubble	15x15	3.1 (4)

[a]*:On source time based on number of tiles (see fig 5) at 50 minutes/tile (see text).*

Analysis: Resulting [CII] line spectra will be used to construct velocity channel and position-velocity maps that will form the basis of our analysis of the kinematics. We will fit line profiles using multicomponent Gaussians to determine surface brightness and identify coherent velocity and cloud structures/components from channel and pv maps. Component masses will be determined from dust column density maps and compared to [^{13}CII] emission (typically after averaging over a larger area). In this way, we can determine the kinetic energy of the gas, which can be directly compared to the thermal energy of the ionized gas and stellar characteristics (wind mechanical energy, luminosity). Cloud structures/components will be compared directly to CO emission, IRAC 8µm and *WISE* 12µm emission due to PAHs, and PACS 70-160µm far-IR dust emission, convolved to the same beam size. These comparisons are at the heart of our (radiative) energy balance analysis as they allow an empirical determination of the [CII]/far-IR, [CII]/CO and [CII]/PAH emission ratios. Physical conditions in these regions will be determined using diagnostic diagrams developed by the team based on plane-parallel PDR models from the PDR-toolbox (htttp://dustem.astro.umd.edu/pdrt/), led by M. Wolfire, and from the clumpy KOSMA-tau PDR model in Cologne (M. Roellig, V. Ossenkopf-Okada). The analysis of the data in the context of irradiated shocks will be led by A. Gusdorf.

Table 2: Lead Investigators:

Source	Lead investigator	Source	Lead investigator	Source	Lead investigator
RCW36	N. Schneider	**NGC6334**	A. Sanchez-Monge	**W43**	J. Bally
RCW79	R. Higgins A. Zavagno	**M17**	J. Stutzki	**Cygnus X**	T. Csengeri, S. Bontemps
RCW49	A. Tielens	**M16**	M. Pound	**NGC7538**	G. Sandell
RCW120	L. Anderson, D. Russeil	**W40**	K. Menten		

Implementation

Team responsibilities: We have assembled a broad team with expertise in [CII] upGREAT observations and data reduction, ancillary data such as *Herschel* & *Spitzer* IR observations and molecular observations, PDR and shock analysis, and supporting theoretical studies. A consortium agreement will form the basis for the team interaction. Overall responsibility for the program resides with the two co-PIs. They provide oversight over all aspects and provide the point of contact to the SSC. Each of the proposed sources has a team leader (Table 2) who will be responsible for the timely analysis, interpretation, and publication of the data for that source as well as for acquiring relevant ancillary data. We have identified a core team, led by R. Higgins, that will be responsible for designing and optimizing the observing strategy for each source and the timely delivery of the level 4 data to the SSC in close consultation with the source team leader. The proposed observations will form the basis for PhD theses at Leiden University, the University of Maryland (through this application) and the data reduction efforts will be supported through a postdoc at the University of Maryland (through this application). Data reduction, analysis, and interpretation will be supported from funding of University of Cologne with one PhD student and one post-doc within the CRC956/A4 and several university staff positions that will devote a part of their time to this project. The GENESIS PIs (Schneider & Simon) will also allocate a significant part of their time to this legacy project since the GENESIS science is closely related to this proposal and the complementary data sets are provided by GENESIS (see below). In case of a successful proposal, a post-doc position that is fully devoted to this legacy proposal will be demanded at the DLR/Verbundforschung. The student and postdoc in Maryland will work in close collaboration with the upGREAT team in Cologne on the level 4 data delivery and the scientific interpretation. Each source included in the sample addresses the objectives of our program in a unique way and we expect that we will write a paper presenting the results for each source separately, placing the [CII] observations in the context of what is known about the source while addressing the unique objectives of that source. Responsibility for these articles resides with the source team leaders.

The projects are well delineated and responsibilities are clear. Success of this highly interwoven endeavor will depend on close collaboration between the scientists involved. The students and postdocs in the team will be strongly encouraged to work closely together to promote cross-fertilization. Interaction between the teams will be fostered through working visits. We will organize yearly team meetings with all team members as well as outside experts to further integrate the efforts.

Scientific community outreach: If granted, we will present the scope, goals, and objectives of this SLP to the wider US scientific community at the Seattle AAS meeting and to the German scientific community at the SOFIA Schloss Ringberg meeting in January 2019. We envision that we will publish, early on, an overview paper on this SOFIA Legacy Program, outlining the goals, objectives, observing strategies, and data reduction plans, and supporting analysis tools. Level 3 & 4 data products will be made available through the SSC data archives as well as through a public website (webmaster: M. Pound) hosted at the astronomy department of the University of Maryland dedicated to the project. The site will inform the astronomical community of the team, sources, and observational status. It will provide easy access to reduced SOFIA data and supplemental data as compiled by team members. In addition, it will provide access to the analysis tools that have or will be developed (see below) by the team.

Analysis and theoretical tools: As part of our theoretical tools, we will upgrade and expand the existing on-line Photodissociation Region Toolbox ("PDR Toolbox" or PDRT) for maps, lines, and models specific to SOFIA capabilities. Mark Wolfire and Marc Pound will be responsible for this aspect. In Cologne, M. Roellig and V. Ossenkopf will apply the KOSMA-tau PDR code for consistency checks. Selected regions will be studied with KOSMA-tau using the more complex setup of a clumpy structure.

The Web Infrared Toolshed (http://dustem.astro.umd.edu) is an on-line analysis suite for infrared and submillimeter line and continuum observations and contains PDRT specifically for the analysis of PDR line emission. PDRT has become the premier on-line site for analyzing PDR observations and allows for a determination of the physical conditions of the emitting gas based upon simple diagnostic diagrams. Upgrades to the PDRT will include returning probability distribution functions for the physical conditions derived from the observations, enabling image data as inputs, incorporating the latest PDR and dust models, adding new diagnostic spectral lines that can be observed with the current and future suite of SOFIA instruments, and expanding the database of pre-run PDR models over a wider range of parameter space. Current diagnostic lines and the SOFIA instruments key to their observations include [C II] (upGREAT,FIFI-LS) [O I]63&145μm (HIRMES,upGREAT, FIFI-LS), H_2 rotational transitions (EXES, HIRMES), [Si II] (HIRMES), [Fe II] (HIRMES). Proposed additions include the [^{13}C II] line (upGreat) and the high J CO transitions (upGreat).

In addition, we will provide a dedicated and extensive grid of shock emission characteristics calculated with the Paris-Durham shock model. These grids allow to accurately determine the physical conditions when shocks play a role in the excitation of the targeted species (OI, CII) as well as other shock tracers (e.g., high-J CO lines). These models will also include the effects of potentially strong ($G_0 > 100$) external irradiation on the observational shock characteristics, using a newly developed code for irradiated shocks. The results will be compared with e.g., the [OI] 63μm observations to determine shock characteristics. Antoine Gusdorf will be responsible for this aspect. The results will be made accessible to the community through our team website as diagnostic diagrams for quick analysis.

We will create a public WEB site (at the University of Maryland) that will provide easy access to reduced SOFIA data as well as maps of I_{IR} and [CII]/$I_{IR.}$ Supplemental data such as Herschel dust temperature and column density maps as and CO data is compiled and provided by the GENESIS project (PI: Schneider & Simon in Cologne, https://www.astro.uni-koeln.de/GENESIS). In addition, we will develop an interface where users can input maps of [CII] line intensity and IR continuum data and retrieve maps of I_{IR}, [CII]/I_{IR}, T_{dust}, and column density. The resulting maps can then be part of the data ingested by PDRT that will return the physical conditions.

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Weaver, R., et al., 1977, ApJ, 218, 377; Williams, J., McKee, C.F., 1997, ApJ, 476, 166
Wolfire, M.G., et al., 1995, ApJ, 443, 152; Wolfire, M.G., et al., 2003, ApJ, 587, 278
Zavagno, A., Anderson, L. D., Russeil, D., et al. 2010, A & A, 518, L101

Principal Investigator and Co-Investigators

co-PI: A.G.G.M. (Xander) Tielens

Tielens will be responsible for general guidance and oversight of the project. He is also the point of contact to the SOFIA Science Center. He will guide the analysis and interpretation of the data by the postdoc and student at the University of Maryland and the students at Leiden University.

Ph.D. 1982, Physics and Chemistry of Interstellar Dust, Advisors: H.J. Habing and L.J. Allamandola

Positions:
Professor of Astrophysics, Univ. of Leiden: 2009 – present
Adjunct professor, Astronomy Department, Univ. of Maryland, 2018–present
Senior Scientist NASA Ames Research Center: 2005 – 2009
Professor of Astrophysics, University of Groningen: 1998 – 2005
Senior Scientist NASA Ames Research Center: 1989 – 1997
Research Associate University of California Berkeley: 1984 - 1989
NRC Associate NASA Ames Research Center: 1982 - 1984

Other affiliations and honors
HJ Allan Award NASA Ames Research Center 1988; Pastoor Schmeits Prize of Dutch Astronomy, 1992; HJ Allan Award NASA Ames Research Center 1992; Miller Visiting Research Professor, University of California, Berkeley, 2002; Caroline Herschel fellow STScI 2009; European Research Council Advanced Grant 2009; Jubileum Professor, Chalmers University, Gotenborg, Sweden 2010; Spinoza award for Science, 2012, Dutch Science Organization, NWO;

Research
Interstellar Medium, Interstellar Dust, Interstellar Molecules, Polycyclic Aromatic Hydrocarbons, PhotoDissociation Regions, Ejecta from Asymptotic Giant Branch Stars, Infrared Spectroscopy

Professional activities (selection)
Project Scientist, HIFI Heterodyne instrument/Herschel Space Observatory (1997-2013); NASA Project Scientist, Stratospheric Observatory for Infrared Astronomy (2005-2007); Coordinator of "The Molecular Universe"; a Marie Curie Research and Training Network funded under the European Commission Framework Program #6 (2004-2008); Coordinator Dutch Astrochemistry Network (2010-present)

Some publications relevant to this proposal:
- Stellar wind feedback and the disruption of molecular clouds, Pabst, C., Higgins, R., Goicoechea, J., et al., 2018, Nature, submitted
- [CII] emission from L1630 in the Orion B molecular cloud, Pabst, C., et al., 2017, A&A, 606, A29
- Interstellar PAH Molecules, Tielens, A.G.G.M. 2008, Annu Rev Astron Astrophys, 46, 289
- Physics and Chemistry of the Interstellar Medium, Tielens, A.G.G.M. 2005, University of Cambridge Press
- Dense Photodissociation Regions, Hollenbach DJ & Tielens, AGGM., 1997, Annu Rev Astron Astrophys, 35, 179
- Photodissociation regions in the interstellar medium of galaxies, Hollenbach DJ & Tielens, AGGM, 1999, Rev Mod Phys, 71, 173

Co-PI Dr. Nicola Schneider

She will be responsible for general guidance and oversight of the project and the integration of the efforts by the German co-Is into the project. She will guide the analysis and interpretation of the data by postdocs and students at the University of Cologne.

https://hera.ph1.uni-koeln.de/~nschneid/
2011 Habilitation (University of Bordeaux, France)
1995 Ph.D. (I. Physik. Institut, University of Cologne, Germany)

Positions
Senior scientist, Univ. of Cologne: 2015 – present
Senior Scientist, LAB Bordeaux: 2012 – 2015
Researcher-engineer, CEA Saclay: 2006 – 2012
Research associate, LAB Bordeaux: 1999 – 2005
Research associate, LAOG Grenoble: 1998 – 1999
Research associate, KOSMA, Univ. of Cologne: 1995 – 1998

Research
Interstellar medium, molecular cloud formation, star formation.
Stellar feedback (photodissociation regions and shocks, formation of pillars, globules)
Long-lasting observational experience in ground-based, airborne, and space-borne submm/FIR astronomy.

Professional activities (selection)
PI of the DFG/ANR (german-french) project GENESIS. PI of program 'Pillars' (Herschel open time). Co-I of Cygnus X Spitzer legacy program. Co-I of Herschel keyprograms (HOBYS, Gould Belt, Hi-GAL)
Active member of the GREAT team, participating in observations preparation and flights. PI and co-I of more than 10 (up)GREAT projects, including the first detection of the CII line in a high-latitude diffuse cloud, the first detection of a THz water maser, and the study of massive star-forming regions.

Selection of recent publications (SOFIA based publications are underlined):

- *Anatomy of the massive star-forming region S106*
  Schneider N., Roellig M., Simon R, et al., 2018, A&A in press, arxiv:1806.00991
- *First detection of THz water maser in NGC7538-IRS1 with SOFIA*
  Herpin F., Baudry A., Richards A., Gray M., Schneider N., 2017, A&A 606, 52
- *Globules and Pillars in Cygnus X: I. FIR-imaging of the Cyg OB2 environment*
  Schneider N., Bontemps S., Motte F., et al., 2016, A&A, 591, 40
- *SOFIA/FORCAST observations of warm dust in S106: a fragmented environment*
  Adams J.D., Herter T., Hora J., Schneider N., et al., 2015, ApJ 814, 54
- *The impact of compression by ionization on thedensity structure of molecular clouds*
  Tremblin P., Schneider N., et al., 2014, A&A 564, 106
- *Pillars and globules at the edges of HII-regions*
  Tremblin P., Minier V., Schneider N., et al., 2013, A&A 560, 19
- *Globules and pillars seen in the [CII] 158 mum line with SOFIA*
  Schneider N., Guesten R., et al., 2012, A&A 542, L18
- *Ionized atomic carbon and high-J CO spectral lines in S106*
  Simon R., Schneider N., et al., 2012, A&A 542, L12

Vitae co- Investigators

Loren Anderson is an associate professor in the physics & astronomy department at West Virginia University. His research focuses on the distribution of Galactic HII regions and their effects on the ISM. He has extensive experience with far-infrared studies of HII regions as a member of the Herschel HOBYs team, has led numerous studies of the Spitzer and WISE emission from HII regions, and has been PI for Herschel studies of HII regions and successful SOFIA cycles 4 and 5 upGREAT [CII] observations of the HII region S235. He will lead the analysis of the RCW120 region.

John Bally is a professor at the University of Colorado in Boulder. John investigates the role of feedback in the self-regulation of star formation. He has extensive experience in the study of protostellar outflows, shocks, and the role of UV radiation in cloud disruption using data from visual to millimeter-wavelengths. He has obtained multi-spectral data sets of many star forming complexes and HII regions such as Orion, W3/4/5, NGC7538, W43, W51, Sgr B2. We was a co-I on the Herschel Space Observatory Galactic Plane Survey (Hi-GAL) and the CARMA-Nobeyama interferometric survey of the Orion A molecular cloud (CARMAOrion). He continues to work on massive star and star cluster formation in extreme environments such as the Central Molecular Zone and the most massive star forming regions along the Galactic plane. He has studied W43 over many decades and he and his student will lead the analysis and interpretation of this source.

Sylvain Bontemps is a staff member at Laboratoire d'astrophysique, Bordeaux, France. He is the PI of the ANR/DFG program, GENESIS, and was co-coordinator of the Herschel imaging Key Program, HOBYS, that focused on massive star formation and that is at the basis of this proposal. He is an expert in the Cygnus X region (>10 publications) and will work with T. Csengeri on the exploitation of the data on this source.

Timea Csengeri is a Post-Doc at MPIfR Bonn and employed as permanent researcher at LAB Bordeaux at the end of the year. She is experienced in submm/mm astronomy with main interest in Galactic high-mass star-forming regions and PI and co-I of many SOFIA/GREAT observations and data analyst for GREAT. She will be together with S. Bontemps responsible for the Cygnus X region (more than 10 common publications on this region).

Rolf Guesten has been the Head of the Division for Submillimeter Technologies at the Max-Planck-Institut für Radioastronomie (MPIfR), where among other things he is the P.I. of the GREAT instrument, a senior Herschel scientist and P.I. of the Herschel-HEXGAL program, and has primary responsibility for German operations of the APEX telescope. Dr. Guesten has been (co-)author on more than 35 publications based on SOFIA/GREAT data. He will help coordinating the observing schedule for the Cycle 7 GREAT observation and the GREAT instrument Configurations, and (partly) supervise the observations. He will coordinate and supervise a complementary observing program with the APEX, adding, among others ^{13}CO and atomic CI data.

Antoine Gusdorf is a research scientist working at LERMA, Paris Observatory and the Ecole Normal Superieure, in Paris. His expertise includes shock physics and chemistry, from the observational and modeling points of view. He has published 4 articles based on the comparison of shock models with observations by SOFIA/GREAT as a first author, and has participated to 7 other published studies based on SOFIA/GREAT observations. He will be in charge of comparing the observations with models of irradiated shocks developed in his laboratory, when necessary. He will also make sure that all shock model grids run in the frame of this study are made available to the public.

Ronan Higgins (Universität zu Köln) is a post doctoral researcher. He previously worked as a calibration scientist on the Herschel/HIFI instrument where he played a leading in role determining the instrument response and resolving instrument data quality issues. He has flown multiples time on SOFIA where his main roles are the upGREAT data calibration and observing support. He has recently led the observing and reduction of the largest velocity resolved C + map taken to date of the Orion A region. He will lead the data reduction team, guiding the Univ. Maryland & the Univ of Cologne postdocs in the preparation of the level 4 data products. He will also lead the analysis and interpretation of the RCW79 source.

Slawa Kabanovic (Universität zu Köln*)* is a second year graduate student. He is a member of the upGREAT team and flown on multiple SOFIA flights. The topic of his thesis is opacity effects in the [CII] line determined through [13CII] observations. He has worked on the [CII] opacity analysis of the Orion A map and has developed a useful set of tools in the process. He will support the data reduction and will look at opacity effects across all sources.

Karl M. Menten is the director for Millimeter and Submillimeter Astronomy at the Max Planck-Institut for Radio Astronomy (MPIfR) and the principal investigator of the Atacama Pathfinder Experiment (APEX). He has extensive experience on radio and (sub)millimeter wavelength observations. His group at the MPIfR has conducted various large scale surveys with the APEX. These cover various CO transitions, providing complementary molecular line data. Menten also is the PI of a large scale survey of the Galactic plane at radio frequencies (4--8 GHz) with the K. G. Jansky Very Large Array (VLA). Delivering data of the radio continuum emission and recombination lines this survey provides complementary information on the structure and kinematics of the fully ionized material (HII regions) for M17, M16, W40, W43 and the Cygnus X region. Its angular resolution of 10" is well matched to that of our SOFIA [CII] data.

Yoko Okada (Universität zu Köln) is a post doctoral researcher. She is in the upGREAT team and has flown and will fly on SOFIA to support observing. She is leading the [CII] and [OI] maps in the LMC and IC1396 in the upGREAT guaranteed time projects. In this proposal, her main role is to support detailed observing strategies and data reduction on the technical side, and to participate the analysis and interpretation of the M17 data on the science side.

Volker Ossenkopf-Okada (Universität zu Köln) is an expert of PDR modelling. He is PI of the project ``Modelling of Irradiated Molecular Clouds" within the DFG-funded SFB 956 in Cologne and was PI of the Herschel key project on PDRs (WADI). He will contribute to the interpretation of the details of the line intensities through the comparison with chemical PDR models.

MSc *Cornelia Pabst* is a third year graduate student at Leiden Observatory. The proposed observations will be part of her thesis studies. She has extensive experience with [CII] observations taken with upGREAT/SOFIA. She was responsible for the data analysis and interpretation of the upGREAT study of the L1630/Horsehead region and Orion. She will devote 100% of her time to the analysis and interpretation of the upGREAT [CII] data.

Marc Pound is a Principal Research Scientist at the Astronomy Department of the University of Maryland. He has an active research program in mm/submm astronomy, specializing in the dynamics of gas at the boundaries of HII regions and molecular clouds. He has extensive experience in software design and development, and management of software teams with a successful record of product delivery. He is the Principal designer and developer of the Web Infrared Toolshed. He was head of the software group for the Combined Array for Millimeter-Wave Astronomy (CARMA) 2010-2015, with responsibility for management of the overall software effort including schedule, deliverables, and task assignments. He was co-developer of CARMA control system and correlator software. He will devote 0.25 FTE to the project and will lead the management of the team web page, and the analysis and interpretation of the M16 source.

Markus Roellig of University of Köln, Germany, is an expert of the chemical and thermal balance modelling of star forming regions. He supports and develops the Cologne PDR model code KOSMA-tau and will provide his PDR modelling expertise to the project.

Delphine Russeil, Laboratoire d'Astrophysique de Marseille/Marseille University, Assistant Professor. Research focuses on the study of massive star-formation and Halpha observations of HII regions. Member of the HOBYS/Herschel key program, leading studies of the NGC 6334/6357 complex.

Alvaro Sanchez-Monge is a post-doctoral researcher at the University of Cologne. He is an expert in mm and submm observations and has strong expertise in the processing and reduction of data taken with ground based telescopes including interferometers like ALMA. He has been the PI of several observational projects using APEX, IRAM30m, VLA or ALMA, a number of them targeting the NGC6334 star-forming complex in different tracers from ionized gas to dense gas. He will be involved in the analysis of the data of NGC6334.

Göran Sandell (Ph.D. Chalmers University, 1979) is a Research affiliate at the Institute for Astronomy, University of Hawaii, Hilo. He worked at the SOFIA Science Center for 18 years. He as a senior advisor and the community scientist for GREAT for both the US and German community. Now he is doing full time research, focusing on SOFIA observations. He has published 11 SOFIA papers, several on [CII] observations of PDRs. He is first author on three of them.

Robert Simon is a senior scientist at the Universität zu Köln and a member of the GREAT instrument team. His research interests and experience are in star formation studies of the ISM, large scale surveys of Milky Way molecular clouds from mm- to submm/FIR wavelengths, PDRs, and InfraRed

Dark Clouds. As an experienced SOFIA/(up)GREAT observer, he will help with the preparations of the observations, the data reduction, and the analysis and interpretation.
Jürgen Stutzki is full Professor of Physics at the Universität zu Köln. He is GREAT principal investigator. His primary research interests cover astrophysics of the dense ISM (turbulent structure, chemical and physical processes; star formation), numerical modeling (radiation transfer, PDR models) and submm and FIR-astronomical instrumentation. He will be responsible for the M17 observations and for supervision of the associated PhD students in Cologne.
MSc *Maitreyee Tiwari* is a second year doctoral student at Bonn University performing her dissertation research at the MPIfR. Her thesis centers on the prominent HII region M8 and its associated PDR and molecular cloud. She has extensive experience with data for the [CII] and high-J CO lines taken with upGREAT/SOFIA and for [CI] and multiple CO lines taken with the APEX 12 meter and the IRAM 30 meter telescopes.
Mark Wolfire is a principal research scientist at the astronomy department of the University of Maryland. He is world-leading expert in PDR modeling and has published extensively on this subject. He has been PI and co-I on a number of Spitzer/IRS and Herschel/PACS&SPIRE proposals focusing on the characteristics of PDRs. He will provide theoretical support for the analysis and interpretation of the data and will assess the implications of this study for models of PDRs. He will provide daily supervision of the research by the student at the University of Maryland. He will devote 0.25 FTE to the project. He is the US lead co-I.
Annie Zavagno is a professor at the Aix-Marseille Université and senior member of the Institut Universitaire de France. She has a 25 years of experience in the study of star formation. She is a specialist of the star formation triggered by the expansion of ionized (HII) regions. She is (co)-author of 110 refereed papers. Her main scientific interests focus on the physics of HII regions and the early phases of high mass star formation. She has a long experience in the analysis of imaging and spectroscopic infrared data, including space-based data (ISO, Akari, Herschel).