Securing Far-Infrared Metal Abundances in NGC 6946

1 — Scientific Context

Context: The heavy element abundance of gas in galaxies strongly influences their evolution, and provides a vital constraint on modern galaxy simulations. Most of the star formation in the Universe takes place under cover of dust, yet virtually all of the metallicity measurements to date use optical-wavelength tracers which are subject to dust obscuration and strong temperature-related uncertainties. We propose a program to develop far-infrared tools which can track absolute metal enrichment across cosmic time, free from the biases imposed by unknown nebular temperature structure and dust obscuration.

Aims: Combining SOFIA measurements of 3 key abundance-sensitive fine-structure lines with a powerful suite of ancillary metallicity data in a sample of nearby galaxy H II regions, we can 1) develop infrared fine-structure lines into powerful new direct and empirically validated tools for charting the full chemical enrichment history of the Universe, and 2) resolve a decades-old fundamental uncertainty in the absolute gas metal abundance scale.

Methods: We map the ground-state fine-structure emission lines of the O^{++} ion — the dominant coolant of ionized gas — together with the fine-structure emission of N^{++} — another powerful indicator of metal enrichment. In this program, we target 8 regions in NGC 6946, a nearby, bright, spiral galaxy, with abundances exceeding solar.

Synergies: Crucially, we are linking our program to the ongoing CHemical Abundances Of Spirals (*CHAOS*) Survey. With tens to hundreds of individual faint *auroral* line detections per galaxy, enabling temperature-corrected *direct* gas metal abundances, CHAOS is delivering roughly an order of magnitude increase in sample and sensitivity over *all prior optical abundance surveys combined*. Our ancillary datasets also include deep optical filled IFU spectroscopy to bridge the resolution divide between SOFIA and CHAOS, Spitzer/IRS maps, with powerful density diagnostics, and even VLA *free-free* 3–33 GHz maps for IR/Radio-only direct abundances.

Results: When complete, this program will provide new and carefully calibrated abundance measures drawn utilizing the power of bright FIR fine-structure lines. In addition, the combination of class-leading optical and FIR spectroscopy will provide unique new probes of temperature structure of ionized nebulae, and help resolve decades-old systematic uncertainties in the absolute abundance of heavy elements in the Universe.

2 — Scientific Justification

Today, despite billions of years of accumulation, elements heavier than helium make up less than one-third of one percent of the mass of the Universe. And yet, this diminutive fraction of the cosmic mass budget makes incredibly powerful contributions to the physical properties and evolution of galaxies and the stars within them. The strong physical impact of metal content on galaxy evolution is remarkably clear in the present day Universe, with many robust metal-driven physical processes uncovered, including the tight relations among a galaxy's gas-phase metallicity, stellar mass, luminosity, and star formation rate (e.g., Tremonti et al. 2004; Cresci et al. 2019), the relative abundance and physical properties of its dust content (e.g., Engelbracht et al. 2005), the excitation conditions and structure of its molecular clouds (Bolatto et al. 2008), and the balance of heating and cooling in its neutral gas (Smith et al. 2017). Galaxies grow in an evolving equilibrium between accretion from circum-galactic gas, star formation, and powerful galactic outflows, and metals provide a unique and direct tracer of these baryon cycling processes. Metallicity is thus emerging as one of the key physical parameters in modern galaxy evolutionary frameworks (e.g., Davé et al. 2019).

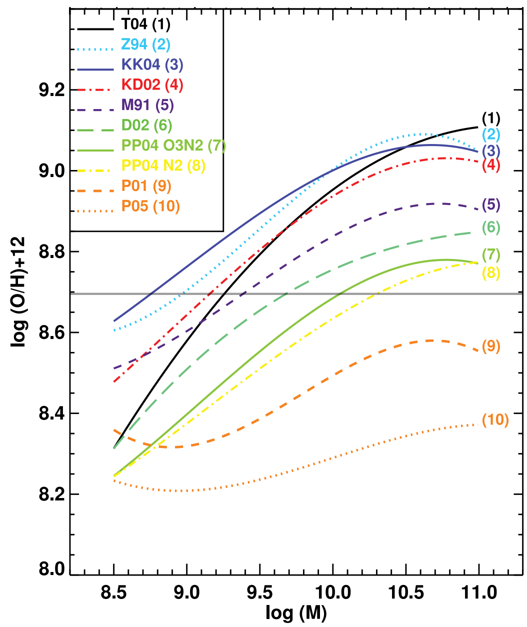

Figure 1: The central locus of the mass-metallicity (MZ) relationship derived from $>10^4$ SDSS galaxies, using a variety of different *strong line* optical metallicity measures. Abundances tied to photoionization models are highest, with empirically-tied calibrations lowest. The gray horizontal line shows the solar oxygen abundance, and demonstrates the current factor of ~ 3–$5\times$ uncertainties in assessing gas phase metal abundance in the Universe. Adapted from Kewley & Ellison (2008).

Background: Despite the rapid pace of new observational and theoretical insights, the absolute chemical enrichment history of the gas in galaxies remains elusive. In part, this is purely an observational limitation — the typically-employed rest-frame optical indicators become challenging to observe from the ground, as they redshift into infrared passbands. More significantly, the strong emission lines used in current and planned abundance surveys retain the same decades-old systematic uncertainties impacting their conversion to underlying metal abundances. Figure 1 illustrates this point dramatically. The celebrated relationship between stellar mass and metallicity in galaxies — which provides deep insights into the interplay between metal production in stars, metal-rich outflows, and pristine inflows of fresh material across a wide range of galaxy mass — suffers major systematic abundance uncertainties depending on the adopted calibration. This results in a nearly unbelievable situation. **We do not yet know whether the gas in the galaxies of today's Universe is predominantly super-solar or sub-solar in its heavy-element abundance** (e.g., López-Sánchez et al. 2012). And even to the extent that temperature-related calibration uncertainties can be overcome, most of the star formation in the Universe has occurred in highly-obscured regions, in galaxies with infrared luminosities and extinction akin to local luminous and ultra-luminous IR galaxies (Whitaker et al. 2017; Elbaz et al. 2018), inaccessible to UV and optical abundance tools.

In the past decade, incredible progress has been made charting the evolution of galaxies in the Universe — the joint growth of stellar and central massive black hole mass (e.g., McConnell & Ma 2013), the bimodal separation of star formation into distinct *modes* with divergent gas consumption timescales (e.g., Elbaz et al. 2011), and the accumulating reservoirs, production pathways, and physical conditions of gas and dust at the earliest epochs (e.g., Decarli et al. 2016). **The next great challenge in understanding how galaxies form and evolve is uncovering the chemical enrichment history of the Universe** — learning both *when* and *how* heavy elements appeared within galaxies and cycled through their halos. The unique gas-cooling lines accessible only to SOFIA, Herschel, and potential future FIR missions such as SPICA and

Origins, will play a major role in meeting this challenge.

Abundance and Temperature: The measurement of the metal abundance of ionized gas is, in principle, straightforward. A bright emission line of a suitable species is identified. With knowledge of the rate by which the line's upper level is collisionally populated (which depends on density and temperature), a weighted measure of the ion's abundance is determined. By measuring a bright hydrogen recombination line nearby ($H\beta$ is typical), a temperature- and density-dependent measure of the abundance of hydrogen is similarly obtained. The density dependence is nearly identical, so their ratio gives an estimate of the relative abundance of the ion to hydrogen. Unfortunately, ionic collisional emission and hydrogen recombination have very *different electron temperature* dependencies (the former rates increasing with temperature, the latter decreasing). So to measure abundance accurately, it is usually essential to estimate temperature. This is commonly performed using faint additional lines of the same ion which arise from yet higher energy states, yielding line flux ratios which are highly temperature dependent. But these lines are ~100× fainter and rarely available, leaving strong-line metallicities highly uncertain.

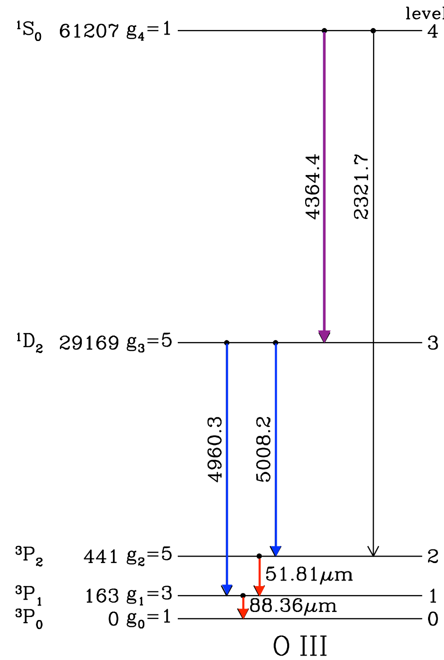

Figure 2: The energy level diagram of O^{++}, with the strong optical cooling lines in blue, the weak auroral 4364Å line — critical for assessing electron temperature — in violet, and the far-infared 52/88 μm ground state triplet lines proposed for study here in red. The excitation temperature is shown at left (K, not to scale), emphasizing the low $T_e \ll 500$K required to collisionally excite the infrared fine-structure lines.

The power of FIR FS lines: Since they arise from low-lying states which ionized gas of any temperature readily excites, *far-infrared ground-state fine-structure transitions* of the dominant ionized gas coolants can *entirely sidestep* this long standing temperature uncertainty. These bright infrared lines are unaffected by dust extinction, and are increasingly accessible in the early Universe, where they redshift into submm bands. In fact, ALMA has recently detected one of our target lines, [O III] 88 μm, in a handful of star-forming galaxies in the era of re-ionization, including in the **earliest spectroscopically confirmed galaxy** at $z = 9.1$ (Hashimoto et al. 2018). Locally, FIR line indicators of metal abundance are also being employed in the dustiest galaxies such as ULIRGs, where no optical lines can penetrate (Herrera-Camus et al. 2018). Since they span a wide range of excitations, the combination of bright FIR and optical lines offers a particularly attractive opportunity to constrain and characterize the temperature properties of nebulae.

Multiple FIR Abundance Methods: With our large ancillary data set, we can simultaneously probe multiple techniques, comparing them with state of the art traditional optical direct abundances: **1)** *direct* temperature insensitive abundances of O^{++}, with optical or mid-IR ionization correction functions and optical H-recombination to normalize Hydrogen column (as in Croxall et al. 2013), **2)** similar direct methods but using *free-free* continuum from the Star Formation in Radio Survey (SFRS, P.I.: E. Murphy) as an extinction-free hydrogen normalization, **3)** blended optical-FIR methods combining the bright lines from both to estimate and correct optical abundances for temperature, **4)** the FIR-only abundance tracer *O3N3*.

Nagao et al. (2011) proposed an FIR-only abundance, which was further explored using Herschel data by Pereira-Santaella et al. (2017): $\mathrm{O3N3} = (2.2 \times [\mathrm{O\,III}]88 + [\mathrm{O\,III}]52)/[\mathrm{N\,III}]57$. Physically, *O3N3* derives its abundance sensitivity from the fact that nitrogen is both a primary and secondary species; it is produced in quantity through non-conserved catalysis in the CNO cycle, and released when those stars evolve off the main sequence. Since metal content and stellar cycling are linked, the N/O ratio provides a valuable surrogate for metal enrichment. Figure 4 shows our own compilation of the complete but quite small set of *O3N3* sources available in the Herschel archive with accurate, temperature-corrected uncertainties.

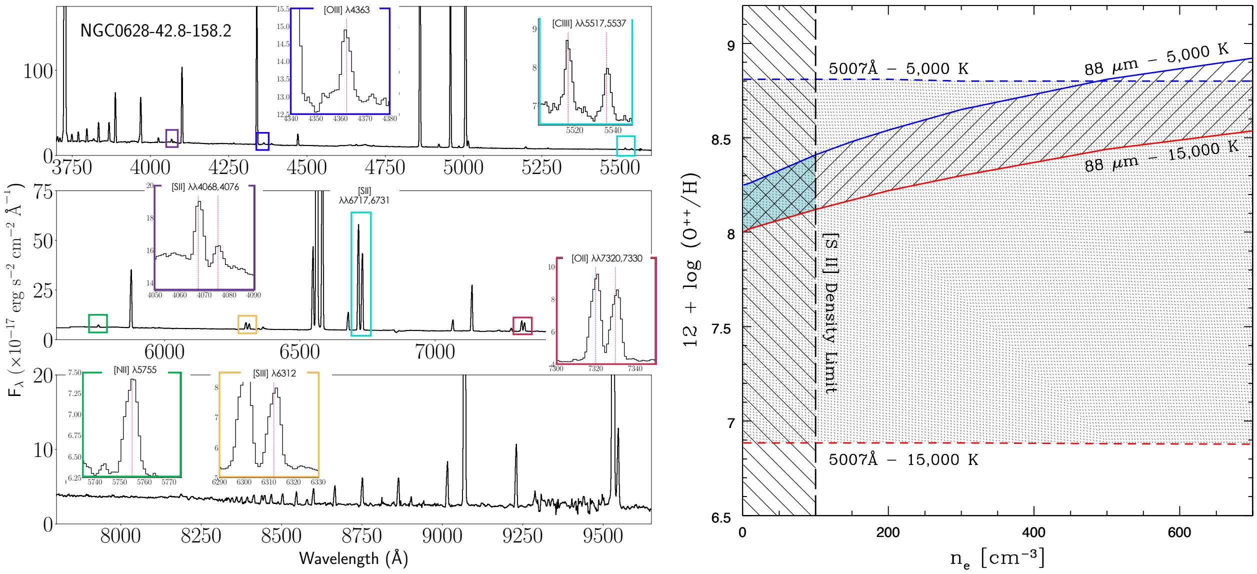

Figure 3: At left, an example CHAOS spectrum of an H II region in NGC 628 (adapted from Berg et al. 2015). Color-coded insets show the many faint *auroral* lines used to estimate temperature, and turquoise boxes highlight density diagnostics. The H II regions in NGC 6946 that we target here with FIFI-LS will be simultaneously targeted by CHAOS, yielding similar spectra to those presented in the figure. At right, an illustration from Croxall et al. (2013) of the range of inferred ionic O^{++} abundance for a single measured line (optical or infrared) as a function of temperature. The modest density dependence of the infrared lines is easily corrected for and is considerably smaller than the strong temperature dependence of the optical lines.

Unlike SOFIA/FIFI-LS, Herschel/PACS could not access the [O III] 52 μm line, so this comparison required estimating the density to determine the [O III] 88/52 ratio. Additionally, the pair of galaxies near solar metallicity in Figure 4 have no reliable temperature-corrected metallicities; only approximate strong line values are shown. SOFIA and CHAOS together will put this powerful new tool on secure footing.

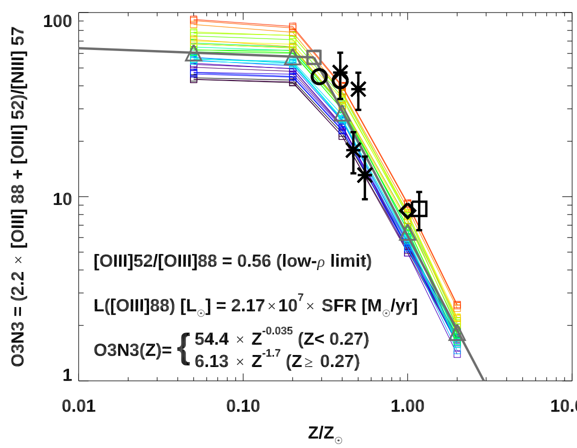

Figure 4: The *O3N3* pure-FIR abundance tracer in local galaxies, with model curves from Pereira-Santaella et al. (2017) (colored lines). At present, only $\sim$ 5 galaxies have both direct, temperature-corrected abundance estimates together with the necessary [N III] 57 μm detections. Two of these are SOFIA/FIFI-LS detections of low-metallicity starbursts (circles, G. Stacey private communication). The two points near $Z{=}Z_\odot$, the luminous galaxies M82 and Arp299, have only strong-line metallicity estimates.

Prior Work: Using Herschel/PACS measurements of [O III] 88 μm in 7 H II regions of NGC 628, Croxall et al. (2013) established the power of the [O III]88 μm fine-structure line for probing metal content. By combining those data with IFU maps from the pPak/PINGS survey, they presented the first ever *direct* temperature-insensitive far-infrared extragalactic abundance measurements, and, intriguingly, found absolute 12+log(O/H) values directly *between* the two divergent strong-line optical calibrations (one tied to photoionization models, another to empirical direct measurements). As can be seen in Fig. 3 (right), FIR lines suffer much lower temperature sensitivity, and only mild density dependence, easily corrected with e.g., mid-IR [S III] or [S II] 6717,6731 lines from our optical IFU maps.

Our proposed SOFIA program would expand the method of IR abundances to a new source, targeting NGC 6946 beyond what was possible with Herschel/PACS, both in terms of areal coverage, and, for selected regions, adding the [O III] 52 μm and [N III] 57 μm lines, to put on secure footing an important FIR line-only metal tracer. The targeted H II regions within NGC 6946 are simultaneously being observed as part of the CHAOS survey, such that optical direct-abundance measurements will be available for comparing to the FIR-abundance experiments proposed here.

3 — Program Feasibility

Our goal of placing far-infrared metal abundance tools on a secure footing is strongly enabled by the capabilities of SOFIA/FIFI-LS. By mapping 3 key abundance-sensitive fine-structure lines in 8 carefully selected regions in NGC 6946, we will:

1. Expand the coverage in the bright ionized gas coolant [O III] 88 μm, which, together with matched optical spectroscopy, will be used as a direct temperature-agnostic indicator of metal abundance, out to large galactocentric radii ($\sim R_{25}$), and critically in regions of high metallicity, and hence low temperature, where direct optical abundance determinations are most difficult ($12+\log(\mathrm{O/H}) \gtrsim \mathrm{Z}_\odot$).
2. Directly probe temperature structure and fluctuations in ionized gas by combining the multiple weak-line auroral + strong line temperature-sensitive ratios from CHAOS, with the much brighter strong lines from the FIR-accessible ground state of O^{++}, using our IFU data for careful aperture conversions.
3. Bring together all three ingredients of the promising new FIR-line only *O3N3* calibration together with a powerful validated, and temperature-corrected abundance sample.

Targets: Our 8 target regions, together with existing spectroscopic coverage from Herschel/PACS and Spitzer/IRS, are shown in Fig. 6. The ongoing CHAOS survey has allocated new observations to simultaneously target these regions, and will produce $\sim$ 1-3 independent auroral-line temperature-estimates in each. We target 5 regions in all three FIR lines ([O III] 52 μm, 88 μm, and [N III] 57 μm), and 3 more in the brightest line, [O III] 88 μm, considerably expanding on Herschel mapping of this key abundance-science galaxy.

Line Flux Estimates: Where Herschel/PACS maps of the [O III] 88 μm line are available, we estimate the [O III] 52 μm line flux assuming the low-density limit: 52/88=0.56 (the lowest possible value). This is conservative, as early results from G. Stacey's SOFIA program (private communication) as well as the few measurements of both lines available from ISO spectroscopy indicate a somewhat higher line ratio is typical. The flux of [N III] 57 μm is estimated using the model-empirical relationship shown in Figure 4 (grey line and broken power-law fit). Importantly, the [N III] line is expected to be brightest relative to the other lines at the *highest* metallicities, which is where the current calibration is weakest. Where Herschel/PACS maps of the [O III] 88 μm line are not available, we estimate the [O III] 88 μm line flux by scaling from Hα maps observed as part of the SINGS program. The [O III] 52 μm and [N III] 57 μm lines are then estimated as above. See Table 1 for information on predicted line fluxes.

Related Work:

Building upon the work of Croxall et al. (2013), we have begun a program to combine [O III] 88 μm line observations from Herschel/PACS, mid-infrared fine-structure line observations from Spitzer/IRS, multi-band VLA continuum data, pPAK optical-fiber IFU observations, and LBT/MODS high-sensitivity optical-slit spectroscopy, to compare metallicities derived using the different methods outlined in the Science Justification section. Our preliminary results, targeting M101, show that the FIR+free-free abundance determinations agree very well with the CHAOS temperature-corrected optical abundances (see Fig. 5). FIFI-LS, together with the ongoing LBT/MODS

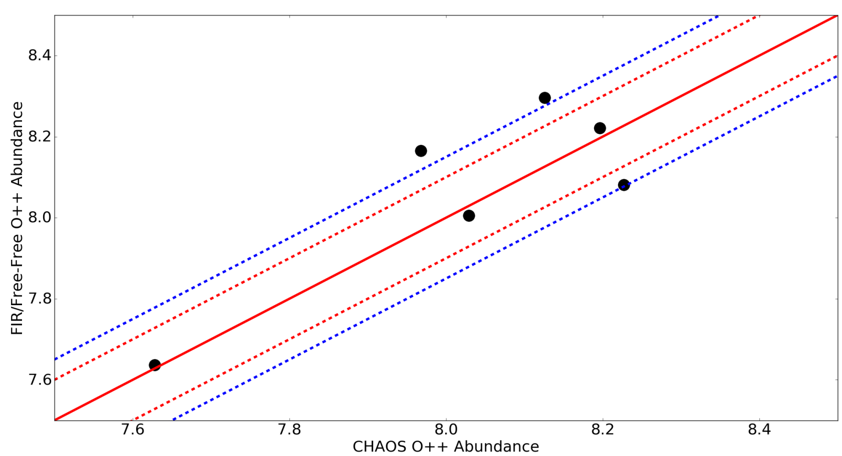

Figure 5: Preliminary work comparing CHAOS temperature-corrected O++ abundance measurements with FIR+free-free O++ abundances in 6 H II regions within M101. The dashed red (blue) lines denotes agreement within 0.1 (0.15) dex.

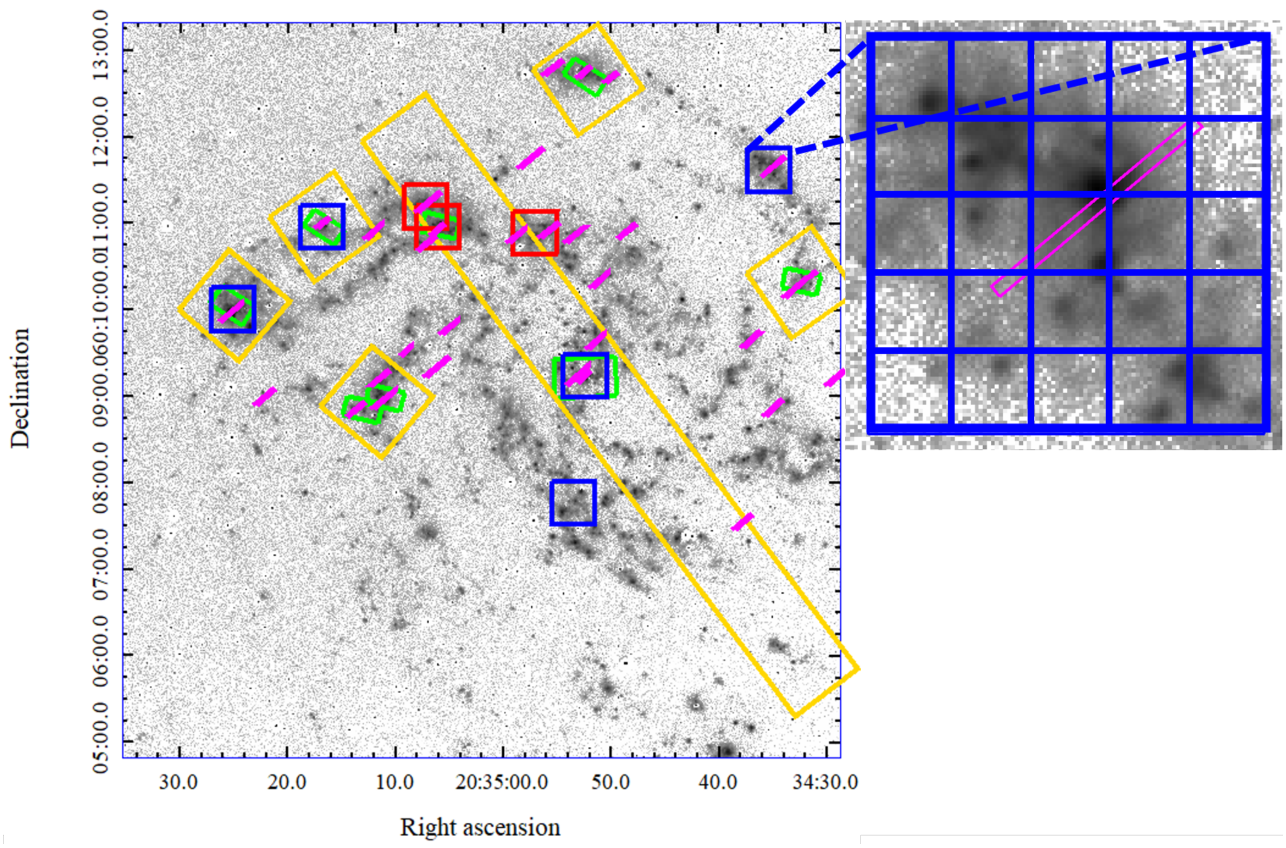

Figure 6: Target galaxy NGC 6946, in Hα from the SINGS program (greyscale). Our 8 target regions centered on the $30'' \times 30''$ FIFI-LS blue-channel FOV are shown as small squares: blue regions are targeted in all 3 abundance-sensitive lines ([O III] 52, [O III] 88, and [N III] 57), while red regions show [O III] 88 coverage. Note that FIFI-LS's red channel FOV is 4× the area depicted. The gold outline denotes prior coverage by Herschel/PACS of [C II] 158 and [O III] 88 in a radial strip and selected extranuclear positions. The green overlays show Spitzer/IRS mapping spectroscopy, with access to the density tracer [S III] 18/33. A single region is zoomed in the inset, revealing the 5×5 grid of $6''$ FIFI-LS spaxels, and the CHAOS LBT/MODS slit (magenta). Note that the 5 blue regions target two spectral lines completely absent from the PACS mapping observations ([O III] 52 and [N III] 57), while the 3 red regions target the [O III] 88 line in regions clipped by the edges of the PACS maps, yielding valuable new data in prime CHAOS-targeted regions.

CHAOS program, will allow us to expand the sample of H II regions with both FIR+free-free and optical temperature-corrected abundances, putting this novel method on firm footing before extending it to high-redshift dusty star-forming galaxies and local ULIRGs, where optical methods become difficult.

Observing Time and Background Removal Strategy:

Given the line estimates described above, we use the FIFI-LS sensitivity calculator to estimate the on-source integration times necessary to achieve SNR=5 on the central spaxel for each of the [O III] 88, [N III] 57, and [O III] 52 μm lines. Examining the physical extent of the H II regions in the Hershel/PACS maps, which have similar angular resolution at 88 μm as does SOFIA/FIFI-LS at 52 μm, we expect an integrated SNR of $\sim$ 7-10 over the inner 3x3 spaxels of the array, for each spectral line observed. With these criteria, our sample of H II regions within NGC 6946 divides nicely into two bins of on-source integration time for the [O III] 88 line (5 and 10 minutes) and three time bins for the [O III] 52 and [N III] 57 lines (10, 15, and 30 minutes). We specify a symmetric chop for all regions. By examining the structure in Hα imagery, we validated that symmetric regions devoid of ionized gas exist within the 4' throw afforded by FIFI-LS at the shortest wavelengths, for each target. The precise position angles and offset will be tuned during Phase II. Adopting 30 second integrations per cycle results in a total program time (including overheads) of 11.9 hours, with $\sim$3.0 hours dedicated to [O III] 88, $\sim$4.45 hours to [O III] 52, and $\sim$4.45 hours to [N III] 57.

Matching Apertures: The success of our program requires tying our observations to CHAOS, the highest quality optical temperature-corrected direct-abundance survey in existence. The various apertures of interest are shown in Fig. 6. The SOFIA PSF is substantially larger than the 1" slit width employed in the CHAOS program on LBT/MODS. A crucial ingredient for our goal of combining temperature-corrected optical and FIR abundance measurements is therefore our significant filled IFU mapping of NGC 6946. While the IFU data do not recover the very faint auroral lines of our CHAOS spectroscopy (see Fig. 3), we will use bright tracers such as [O III] 5007Å and Hβ to correct for relative flux capture in the CHAOS and SOFIA spectral apertures. While we do not anticipate large aperture corrections based on the morphology of the ionized gas, we can eliminate this potential systematic using our fully filled IFU optical spectroscopy.

Red Channel Ancillary Science: While our primary line-targets driving the abundance case are all in FIFI-LS's blue channel, we are also very interested in collecting simultaneous red-channel line data, with 4× the areal coverage. For all observations with the blue channel, in all 8 regions, we target the [C II] 158 μm line in the red channel, with a very high predicted SNR>20. (The [N II] 122 μm line is largely blocked by the atmosphere at the redshift of NGC 6946.) With twice the field of view of the blue channel coverage, our red FIFI-LS coverage of [C II] will offer a highly informative look at the so-called "C+ deficit", which was explored in detail in resolved regions of 45 KINGFISH galaxies in Smith et al. (2017). These new SOFIA [C II] maps will re-image bright H II regions clipped by the edges of the original KINGFISH mapping, as well as cover new H II regions never imaged by Herschel in NGC 6946.

Table 1. Summary of Observations

Region	R.A.	Dec.	Expected Flux (10^{-17} W m^{-2})			On-Source Time (min)		
			[O III] 88 μm	[O III] 52 μm	[N III] 57 μm	[O III] 88 μm	[O III] 52 μm	[N III] 57 μm
Nuc	20:34:52.369	+60:09:13.93	17.0	9.5	9.5	5	15	15
Enuc. 1	20:35:25.129	+60:09:59.73	33.0	18.5	18.5	5	10	10
Enuc. 2	20:35:16.847	+60:10:57.18	11.7	6.7	6.7	5	30	30
Enuc. 3	20:35:07.183	+60:11:11.10	7.2	-	-	10	-	-
Enuc. 4	20:35:06.010	+60:10:57.27	7.2	-	-	10	-	-
Enuc. 5	20:34:57.029	+60:10:52.94	6.4	-	-	10	-	-
Enuc. 6	20:34:35.254	+60:11:36.56	10.6	5.9	5.9	5	30	30
Enuc. 7	20:34:53.415	+60:07:45.82	30.0	16.8	16.8	5	10	10

Note—On-source times are calculated such that we expect to achieve S/N ratios of 5 on the central spaxel for each line, with integrated S/N ratios of $\sim$ 7-10 over the inner 3x3 spaxels. The resulting total observing time (including overheads) for this program is 11.9 hours.

References

Berg, D. A., Skillman, E. D., Croxall, K. V., et al. 2015, ApJ, 806, 16

Bolatto, A. D., Leroy, A. K., Rosolowsky, E., Walter, F., & Blitz, L. 2008, ApJ, 686, 948

Cresci, G., Mannucci, F., & Curti, M. 2019, A&A, 627, A42

Croxall, K. V., Smith, J. D., Brandl, B. R., et al. 2013, ApJ, 777, 96

Davé, R., Anglés-Alcázar, D., Narayanan, D., et al. 2019, MNRAS, 486, 2827

Decarli, R., Walter, F., Aravena, M., et al. 2016, ApJ, 833, 69

Elbaz, D., Dickinson, M., Hwang, H. S., et al. 2011, A&A, 533, A119

Elbaz, D., Leiton, R., Nagar, N., et al. 2018, A&A, 616, A110

Engelbracht, C. W., Gordon, K. D., Rieke, G. H., et al. 2005, ApJ, 628, L29

Hashimoto, T., Laporte, N., Mawatari, K., et al. 2018, Nature, 557, 392

Herrera-Camus, R., Sturm, E., Graciá-Carpio, J., et al. 2018, ApJ, 861, 95

Kewley, L. J., & Ellison, S. L. 2008, ApJ, 681, 1183

López-Sánchez, Á. R., Dopita, M. A., Kewley, L. J., et al. 2012, MNRAS, 426, 2630

McConnell, N. J., & Ma, C.-P. 2013, ApJ, 764, 184

Nagao, T., Maiolino, R., Marconi, A., & Matsuhara, H. 2011, A&A, 526, A149

Pereira-Santaella, M., Rigopoulou, D., Farrah, D., Lebouteiller, V., & Li, J. 2017, MNRAS, 470, 1218

Smith, J. D. T., Croxall, K., Draine, B., et al. 2017, ApJ, 834, 5

Tremonti, C. A., Heckman, T. M., Kauffmann, G., et al. 2004, ApJ, 613, 898

Whitaker, K. E., Pope, A., Cybulski, R., et al. 2017, ApJ, 850, 208

4 — Biography: PI Cody Lamarche

Dr. Cody Lamarche is a postdoctoral research associate at the University of Toledo. He received B.S. degrees in Physics and Mathematics from the University of Vermont and a Ph.D. in Astronomy from Cornell University. His dissertation research focused on studying star formation in high-redshift galaxies through observations of far-IR fine-structure lines of oxygen, carbon, and nitrogen. Currently, he leads an effort to combine far- and mid-IR, radio, and optical observations to develop a temperature-agnostic, and extinction insensitive, metallicity indicator in a sample of nearby galaxies – a metallicity indicator that can be extended to probe high-redshift dusty star-forming galaxies, as well as local ultra-luminous infrared galaxies (ULIRGs). His relevant papers include:

- *CO-DARK Star Formation and Black Hole Activity in 3C 368 at Z = 1.131: Coeval Growth of Stellar and Supermassive Black Hole Masses*, **Lamarche, C.**, Stacey, G., Brisbin, D., Ferkinhoff, C., Hailey-Dunsheath, S., Nikola, T., Riechers, D., Sharon, C. E., Spoon, H., Vishwas, A., *ApJ* **836** 123 (2017)
- *Resolving Star Formation on Subkiloparsec Scales in the High-redshift Galaxy SDP.11 Using Gravitational Lensing*, **Lamarche, C.**, Verma, A., Vishwas, A., Stacey, G. J., Brisbin, D., Ferkinhoff, C., Nikola, T., Higdon, S. J. U., Higdon, J., Tecza, M., *ApJ* **867** 140 (2018)
- *CO and Fine-structure Lines Reveal Low Metallicity in a Stellar-mass-rich Galaxy at z $\sim$ 1?*, **Lamarche, C.**, Stacey, G. J., Vishwas, A., Brisbin, D., Ferkinhoff, C., Nikola, T., Higdon, S. J. U., Higdon, J., *ApJ* **882** 1 (2019)

5 — Biography: co-I's

- Prof. **J.D. Smith** is a professor of astronomy at the University of Toledo. He received his PhD from Cornell University in 2001. Prof. Smith has been a key member of several local and moderate redshift galaxy surveys, including, the *Spitzer Infrared Nearby Galaxies Survey* (SINGS) and *Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel* (KINGFISH).

- Prof. **Evan Skillman** is director of the Minnesota Institute for Astrophysics. He has a BA in Physics from Cornell University and Ph.D. in Astronomy from the University of Washington. He has a long history of contributions to understanding the chemical evolution of galaxies. His main contributions to the proposed program are anticipated to be in the area of gaining a better understanding of the role of temperature inhomogeneities in the derivation of abundances, and will be responsible for coordinating inter-comparison between CHAOS and FIFI-LS spectral data sets.

- Prof. **Danielle Berg** is a professor of astronomy at the University of Texas at Austin, and is an expert at studying the nebular chemical evolution of galaxies, near and far, using the UV-IR. She received her PhD from the University of Minnesota, and led the analysis for the CHAOS project. She will help constrain the physical properties of the HII regions in NGC 6946, and perform detailed modeling comparisons between temperature sensitive Optical-Optical and Optical-FIR ratios.

- Prof. **Gordon Stacey** is a professor of astronomy at Cornell University. He received his PhD from Cornell in 1985. His primary research interests center on studies of star formation and its interplay with the interstellar medium across cosmic time, focussing on far-infrared and submillimeter wavelength fine-structure and rotational line emission from abundant atoms, ions, and molecules. He has been active in far-IR spectroscopy since 1980, having built and used instrumentation on NASA's Lear Jet and KAO airborne observatories, as well as three generations of ground-based submm spectrometers, and will oversee intercomparisons between FIR abundance surveys.

- Dr. **Kathryn Kreckel** is an Emmy Noether group leader at Heidelberg University, Germany, and is an expert on optical IFU spectroscopy in nearby galaxies. Dr. Kreckel will lead the IFU-based efforts to bridge between SOFIA & LBT/MODS spatial resolutions.

- Prof. **Rick Pogge** is a professor of astronomy at The Ohio State University in Columbus. He received his Ph.D. in astronomy and astrophysics from UC Santa Cruz. Prof. Pogge is the project PI for the Multi-Object Double Spectrographs (MODS) instrument deployed on the Large Binocular Telescope (LBT), which enabled the CHemical Abundance of Spirals (CHAOS) survey. He will coordinate the FIFI-LS observations with the ongoing CHAOS observations.

- **Noah Rogers** is a graduate student at the University of Minnesota working on the CHAOS project under Prof. Evan Skillman. He will provide assistance in reducing the CHAOS observations of NGC 6946.