A Survey of Atomic and Ionized Outflows from Massive Protostars

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Introduction

Massive stars govern much of galactic evolution, yet many of the processes which govern the formation of such large stars are still poorly understood, and there are multiple competing theories for formation. This is largely because massive protostars are embedded in thick clouds of gas and dust, which inhibit the gathering of observational constraints. One key difference of massive protostars compared to their low-mass counterparts is the potential for larger protostars to expel much stronger far- and extreme-ultraviolet (FUV & EUV) radiation, which is theorized to occur for the most massive protostars ($M_{star} > 20\ M_\odot$) (Zhang 2014), irradiated by FUV and EUV photons, out-flowing gas can be dissociated and ionized, producing lines that diagnose atomic and ionized phases (Tanaka 2016).

This program surveys 17 massive protostars from the SOFIA Massive (SOMA) Star Formation Survey with the FIFI-LS spectrometer in four far-infrared (FIR) ionized, atomic, and molecular spectral bandpasses.

The objectives of this program are to:

1. Characterize region morphology and identify velocity-resolved bipolar outflow structure
2. Measure continuum photometry and construct spectral energy distributions (SEDs) to inform on protostellar characteristics
3. Investigate the relationship between [OI] line intensity and protostellar bolometric luminosity (and therefore accretion rate)
4. Compare [OI] line intensities to models to estimate outflow rate

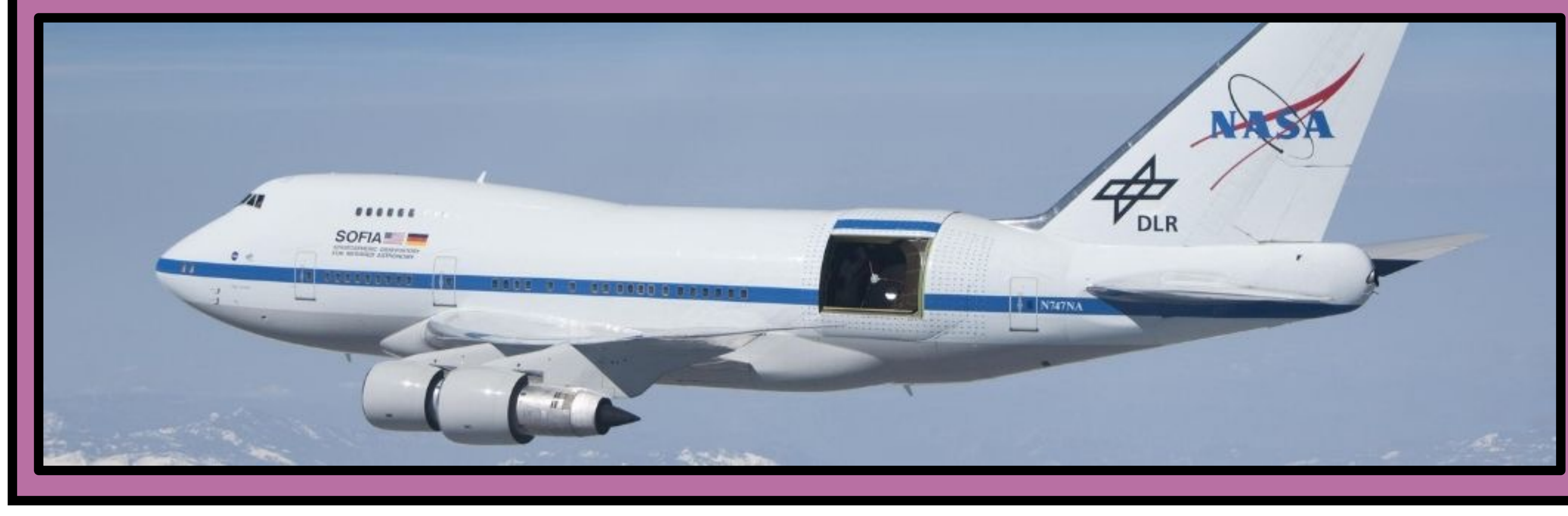

Figure 1. The SOFIA aircraft. Picture credit: Jim Ross.

Methods

The four spectral lines selected for this program are: [OIII] $^3P_2 \rightarrow {}^3P_1$ at 52 µm, [OI] $^3P_2 \rightarrow {}^3P_1$ at 63 µm and $^3P_1 \rightarrow {}^3P_0$ at 145 µm, and CO J = 14 → 13 at 186 µm. We present spectral cubes in all four bandpasses for 17 sources. Spectra were extracted using the *photutils* package from *AstroPy*. FIFI-LS suffers from relatively poor spectral resolution, and nearby telluric features (particularly in [OI] 63 µm) present a challenge for data reduction.

Spectra / Images

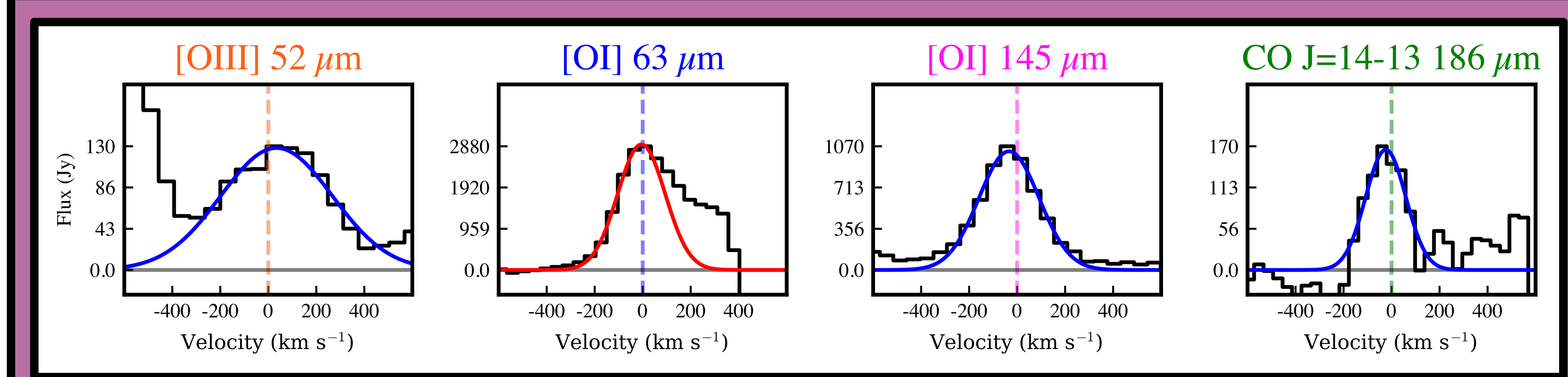

Figure 2. Example spectra from FIFI-LS for the source G011.94-00.62 with 1-D Gaussian fitting performed to measure line intensity. The extended wing in 63 µm [OI] is due to a consistently detected telluric feature, and the Gaussian there is only fit to the left side of the spectrum to ignore it. This particular source possesses the largest FWHMs for any source in the survey, with the [OIII] spectrum possessing a FWHM (deconvolved from the instrumental resolution) of 398.7 km s^{-1}

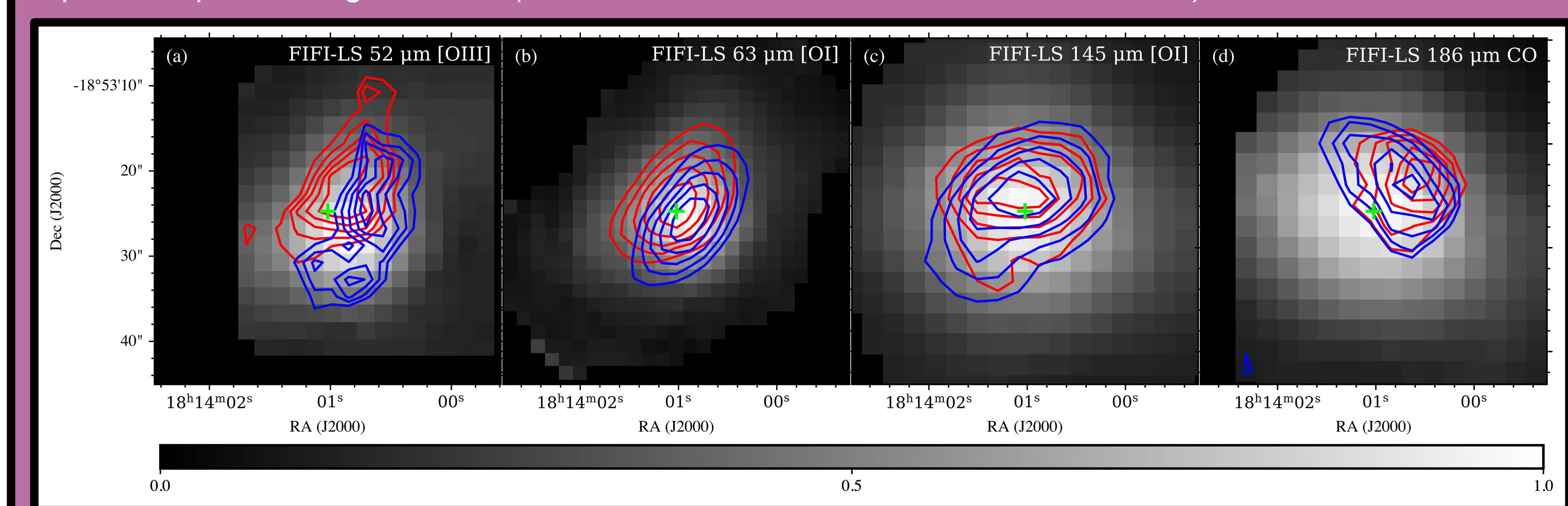

Figure 3. Line emission mapping for G011.94-00.62, with grayscale continuum background. The velocity-resolved structure visible in [OIII] 52 µm and [OI] 63 µm suggests the presence of a poorly collimated bipolar outflow, which has since also been precovered in ALMA ^{13}CO *J = 2 → 1,* $C^{18}O$ *J = 2 → 1, and* $H_2CO\ 3_{03} \rightarrow 2_{02}$*. This source is the first to have its outflow detected through its ionized [OIII] emission and is the subject of its own paper (Oakey in prep).*

Results

We gather background-subtracted photometric measurements within an algorithmically-derived aperture (Fedriani 2023) from each continuum image from FIFI-LS and archival observations from SOFIA, Herschel, Spitzer, and WISE. We then input these measurements into the Python package *SEDcreator* (Fedriani 2023), which fits the SED datapoints with a series of models (Zhang 2018) to inform on protostellar characteristics such as mass and bolometric luminosity.

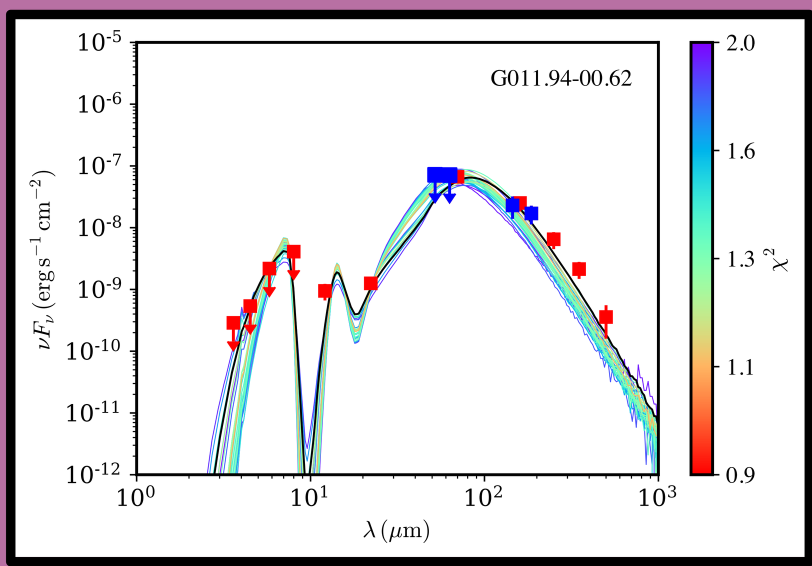

Figure 4. Example SED fit for G011.94-00.62.

We then compare the [OI] line intensity measurements (Figure 2) with estimates for bolometric luminosity derived from SED fitting. It is expected that there will be a correlation between the two parameters if [OI] flux corresponds to protostellar accretion rate (Hollenbach 1984). We find strong agreement in the 145 µm line, which is not as affected by self-absorption as the 63 µm line is.

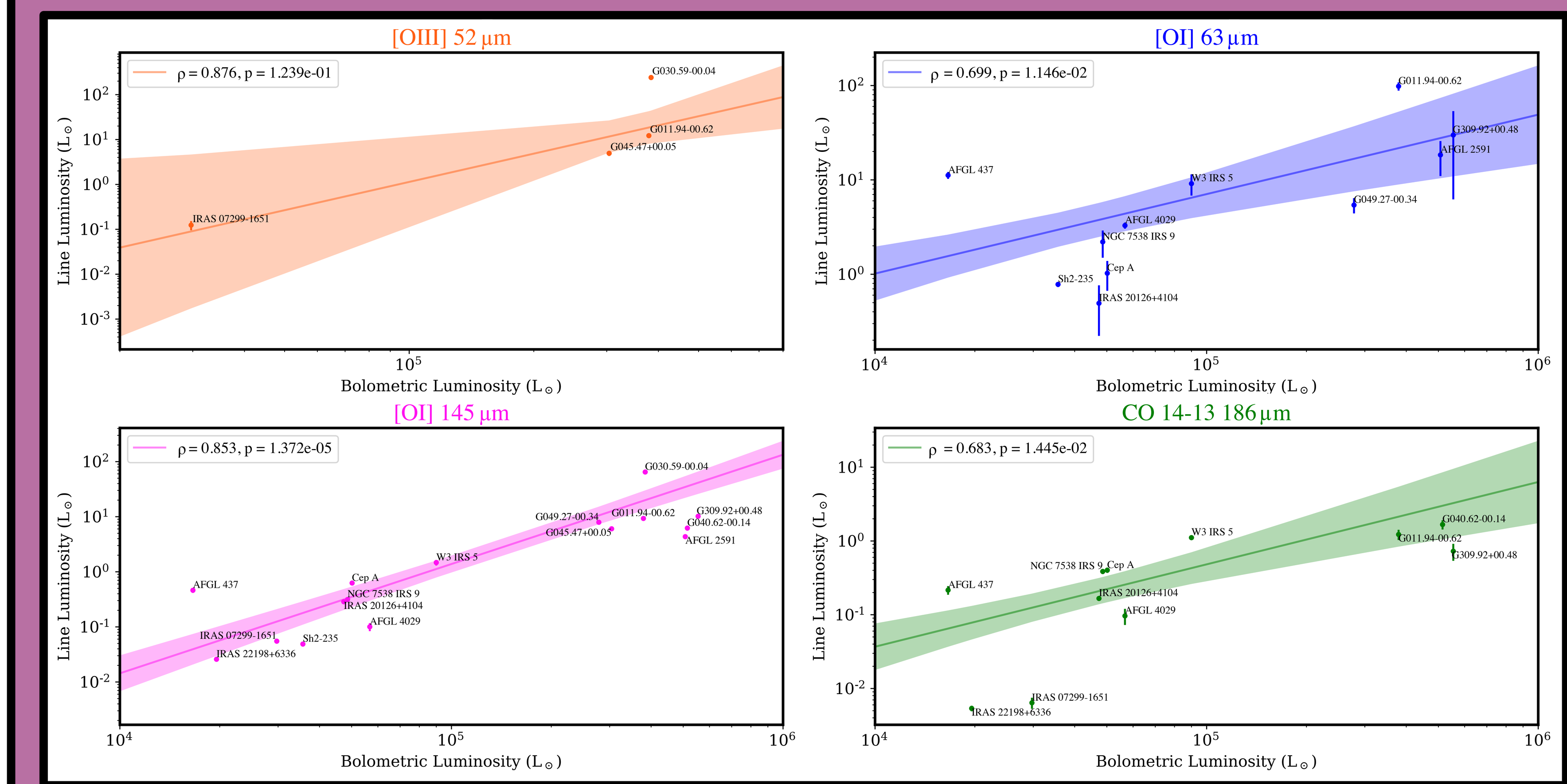

Figure 5. Comparison of line luminosity and bolometric luminosity for each source. There is strong correlation of [OI] in the 145 µm line. The 63 µm line is affected by an unconstrained self absorption feature which is unique for each source and cannot be precisely accounted for.

We run a special 1-D version of the 3DPDR software (Bisbas 2012) to estimate oxygen column density. We take this estimate and extrapolate the total gas mass. Using the gas velocity derived from the spectral FWHM across the length of the outflow to obtain a dynamical time, we then divide the total gas mass by the dynamical time to estimate outflow rate.

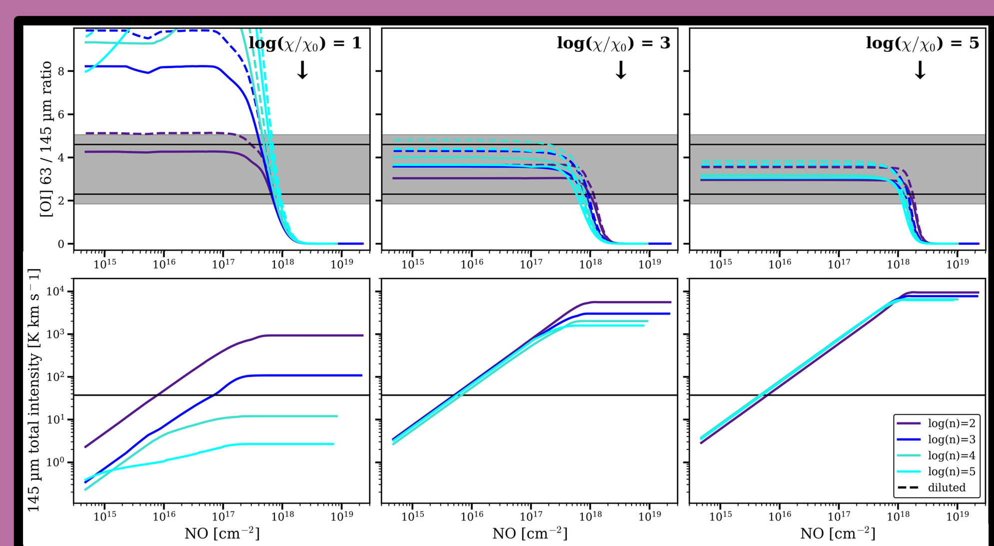

Figure 6. PDR models which predict [OI] column density. The horizontal lines are observed quantities.

Discussion

We find good agreement with the intensity of atomic oxygen and the luminosity of the protostellar environment. This is in strong support of the hypothesis that [OI] flux is a tracer of accretion rate.

We predict protostellar mass, luminosity, and accretion rate from SED modelling for each source and outflow rate from PDR modelling. The relative ratio of the accretion rate to outflow rate is ~ 10:1, which is in line with theoretical predictions.

We detect [OI] from all of our sources and [OIII] from four. There is substantial evidence for outflows detected in eight of our sources. One such source (G011.94-00.62) demonstrates loosely collimated bipolar outflow structure in [OIII].

Citations

Zhang, Y., Tan, J. C., & Hosokawa, T. 2014, ApJ, 788, 166, doi: 10.1088/0004-637X/788/2/166 ■ Fedriani, R. et al. 2023, ApJ, 942, 7, doi: 10.3847/1538-4357/aca4cf ■ Zhang, Y., & Tan, J. C. 2018, ApJ, 853, 18, doi: 10.3847/1538-4357/aaa24a ■ Bisbas, T. G. et al. 2012, MNRAS, 427, 2100, doi: 10.1111/j.1365-2966.2012.22077.x ■ Hollenbach, D. 1985, Icarus, 61, 36, doi: 10.1016/0019-1035(85)90151-4 ■ Tanaka, K. E. I. et al 2016, ApJ, 818, 52, doi: 10.3847/0004-637X/818/1/52