Unveiling the nature of candidate high-mass young stellar objects in the Magellanic Clouds with near-IR spectroscopy

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

As nearby neighbors to the Milky Way, the Large and Small Magellanic Clouds (LMC and SMC) provide a unique opportunity to study star formation in the context of their galactic ecosystems. Thousands of young stellar objects (YSOs) have been characterized with large-scale Spitzer and Herschel surveys. In this paper, we present new near-IR spectroscopy of five high-mass YSOs in the LMC and one in the SMC. We detect multiple hydrogen recombination lines, as well as He i 2.058 μm, H2, [Fe ii], and [S iii] in these highly excited sources. We estimate the internal extinction of each source and find that it is highest for sources with the youngest evolutionary classifications. Using line ratios, we assess the dominant excitation mechanism in the three sources where we detect both H2 2.12 μm and [Fe ii] 1.64 μm. In each case, photoexcitation dominates over shock excitation. Finally, we detect CO bandhead absorption in one of our LMC sources. While this feature is often associated with evolved stars, this object is likely young with strong PAH and fine-structure emission lines tracing an H ii region detected at longer wavelengths. Compared to high-mass YSOs in the Galaxy, our sources have higher bolometric and line luminosities, consistent with their selection as some of the brightest sources in the LMC and SMC.

Key words: stars: formation â€“ stars: massive â€“ stars: protostars

1 INTRODUCTION

The formation and evolution of high-mass stars remains an open question in astrophysics. The recent explosion of Galactic plane surveys has provided an unprecedented view of thousands of actively star-forming clouds throughout the plane of the Milky Way (e.g., Hoare et al. 2005; Urquhart et al. 2008; Schuller et al. 2009; Molinari et al. 2010; Aguirre et al. 2011). Unlike previous, targeted observations, these surveys did not select for a particular star-formation indicator, instead providing an unbiased sample. This large population of clumps has enabled construction of an evolutionary sequence and mass function for high-mass stars (e.g., Svboda et al. 2016).

Galaxy-wide surveys, particularly those that target galaxies external to the Milky Way, allow detailed studies of the association between star formation and environment. Two of the closest galaxies to the Milky Way, the Large and Small Magellanic Clouds (LMC and SMC), are particularly prime for observational scrutiny (e.g., Whitney et al. 2008; Dobbs et al. 2010; Louie et al. 2013; Sewilo et al. 2013; Choi et al. 2015; Lewis et al. 2015; Ochsendorf et al. 2016). The LMC and SMC provide many sources at a uniform distance (~ 50 kpc, Pietrzyński et al. 2013 and ~ 60 kpc, Scowcroft et al. 2016, respectively) in irregular galaxies with favorable orientations. Unlike other extragalactic laboratories, the LMC and SMC are close enough to resolve individual high-mass star-forming regions. Multi-wavelength surveys particularly with Spitzer and Herschel have uncovered a wealth of candidate young stellar objects (YSOs) in both galaxies (e.g., Meixner et al. 2006; Whitney et al. 2008; Meixner et al. 2013; Sewilo et al. 2013; Seale et al. 2014). Hundred of candidate YSOs have been targeted for follow-up observations with the Spitzer InfraRed Spectrograph (Spitzer).
IRS; Oliveira et al. 2009; Seale et al. 2009; Oliveira et al. 2011; Woods et al. 2011; Oliveira et al. 2013; Ruffle et al. 2015; Jones et al. 2017). Spectroscopic data reveal absorption due to molecular ices and silicate dust in the youngest protostars while more evolved sources show fine-structure emission lines and UV-pumped polycyclic aromatic hydrocarbons (PAHs) that are typically excited in H II regions. New observations with the Atacama Large Millimeter/sub-millimeter Array (ALMA) provide maps of the continuum and molecular emission with comparable sensitivity and resolution to observations of Galactic clouds. For the first time, it is possible to resolve individual sites of high-mass star formation within the structured natal gas that characterizes the earliest stages. Recent ALMA observations of multiple high-mass star-forming regions in the LMC show protostars forming in dense, filamentary molecular gas with complex dynamics (e.g., Indebetouw et al. 2013; Fukui et al. 2015; Nayak et al. 2016; Saigo et al. 2017; Wong et al. 2017; Nayak et al. 2018; Naslim et al. 2018).

The most complete view of high-mass star formation in the LMC and SMC requires multi-wavelength observations to construct an evolutionary picture. In this paper, we present ground-based near-IR spectroscopy of five high-mass star-forming regions in the LMC and one in the SMC. We sample high-mass, high-luminosity sources, including the super star cluster (SSC) candidate H72.97-69.39, which was recently identified as a younger analog of 30 Doradus (30 Dor, see Ochsendorf et al. 2017, Nayak et al. submitted). High-sensitivity near-IR spectroscopy with NIRSpec on the James Webb Space Telescope (JWST) will enable a more complete spectroscopic census of a broader range of sources. When combined with on-going surveys with other observatories like SOFIA and ALMA, this provides a powerful opportunity to constrain high-mass star-formation at low metallicities.

2 TARGET SELECTION

We restrict our target list to the brightest sources with Spitzer IRS spectra for ground-based near-IR follow-up. These objects have SEDs dominated by dust emission and features in their IRS spectra that indicate a YSO and/or a compact H II region. We compile source classifications from the literature in Table 1. All of our targets fall into the Kraemer et al. (2002) Group 5 – sources with SEDs dominated by dust emission with a peak wavelength longer than 45 μm — and all have strong emission features likely to trace PAH emission (5.1). Most sources also have strong emission lines detected in the ISO SWS spectra (5.1E). Seale et al. (2009) report similar classifications using a modified version of the Kraemer et al. (2002) scheme. Following the Seale et al. (2009) lexicon, sources with strong PAH emission are labeled “P Group” in Table 1; those that also have strong fine-structure emission lines (in addition to the PAH features) are labeled “PE Group.” Sources with dominant silicate absorption are labeled “S Group.”

More recently, Jones et al. (2017) considered all LMC objects with staring-mode IRS spectra within the SAGE footprint. Using a decision-tree approach developed by Woods et al. (2011), Jones et al. (2017) divide sources into 25 different classes and subclasses (see their Table 3). Most of our LMC targets (4/5) have atomic emission lines suggesting that an H II region has already developed, though they may also have PAH features in their spectra. Defined this way, the H II class of objects includes both young (compact) H II regions and older (more diffuse) regions. The only LMC source without associated H II region emission in our sample is classified as a YSO2. These young sources have removed some of their circumstellar material and are hot enough to destroy icy mantles such that their spectra no longer show ice absorption. We list the Jones et al. (2017) classifications for our targets in Table 1.

Our single SMC target, the N76 YSO, shows silicate absorption in its IRS spectrum, and thus is identified as an ‘S Group’ source by Seale et al. (2009). Applying the decision-tree method, Woods et al. (2011); Ruffle et al. (2015) classify the source as a YSO2 (see Table 1).

3 SPECTRAL ENERGY DISTRIBUTIONS

Broad source classifications for objects with multiwave- length photometry may be obtained by determining their colors (e.g., Bolatto et al. 2007) or fitting models to their spectral energy distributions (SEDs; e.g., Whitney et al. 2008). We list source luminosities obtained from SED fits in the literature in Table 2. New models with more flexible parameters have been published since those literature values were computed (Robitaille 2017). Unlike the previous generation of models which provided uneven sampling of the parameter space and limited complexity, these new models include cold dust emission at longer wavelengths and allows the user to determine the components – disk, envelope, cavity, and ambient medium – included in the model fit to the SED.

Applying the Robitaille (2017) models to the IR SEDs, we find that the best-fitting model for most objects in our sample consists of a central star surrounded by an Ulrich envelope (which has the density structure of a free-falling, rotating, and collapsing envelope, see Ulrich 1976) with a cavity and emission from the ambient medium (the s-ubhmi model set, see Table 2 in Robitaille 2017). Sources that are well-fit with these models most closely resemble the Stage I evolutionary classification for low-mass stars (see Robitaille et al. 2006). We list new estimates of source luminosities, temperatures, and radii in Table 2 and show the best model fits in Figure 2. To use these models, we have implicitly assumed that a single star dominates the flux in each source. Most of our sources are probably unresolved clusters, with multiple stars unresolved in the beam (see, e.g., Bernard et al. 2016; Ward et al. 2016).

4 NEAR-IR SPECTROSCOPY

Near-IR spectra of 6 high-mass YSOs in the Large and Small Magellanic Clouds were obtained with the Folded-Port Infrared Echellelette (FIRE, Simcoe et al. 2013) on the 6.5 m Magellan/Baade telescope on 26 November 2015. Figure 1 shows the locations of our targets within their galactic contexts. FIRE provides continuous wavelength coverage from 0.8 – 2.5 μm with a spectral resolution of R=4800 for our chosen slit width of 0.75″. Data were taken in standard
Near-IR spectra of MC candidate high-mass YSOs

Figure 1. Approximate location of the YSOs targeted in this program shown on three-color Spitzer images of the Large (left; Meixner et al. 2006) and Small (right; Gordon et al. 2011) Magellanic Clouds. White boxes and labels indicate the regions targeted for near-IR spectroscopy. Most regions contain one object, except for N159 where we target 3 YSOs.

Table 1. Source classifications

| Target  | region   | K2002$^a$ | S2009$^b$ | J2017$^c$ | R2015$^d$ |
|---------|----------|-----------|-----------|-----------|-----------|
| J84.703995-69.079110 | LMC/30 Dor | 5.UE | PE$^\dagger$ | HII | ... |
| J72.971176-69.391112 | LMC/N79 | ... | ... | HII | ... |
| J84.906182-69.769472 | LMC/N159 | 5.UE | PE | HII | ... |
| J84.923542-69.769963 | LMC/N159 | 5.UE | PE | YSO2 | ... |
| J85.018918-69.743288 | LMC/N159 | 5.UE | PE | HII | ... |
| J16.280250-71.995194 | SMC/N76 | ... | S$^\ast$ | ... | YSO-2 |

classification from $^a$Kraemer et al. (2002); $^b$Seale et al. (2009); $^c$Jones et al. (2017); $^d$Ruffle et al. (2015)

$^\dagger$ strong fine-structure emission lines and PAH features in the IRS spectrum, see Seale et al. (2009)

$^\ast$ spectrum dominated by 10 $\mu$m silicate absorption, see Seale et al. (2009)

Table 2. Source properties from SED fits

| Source | Name | log(L$\star$)$^a$ | M$\star$ | R$\star$ | T$\star$ | log(L)$^b$ | ref |
|--------|------|-----------------|---------|---------|---------|----------|-----|
| J84.703995-69.079110 | 30 Dor YSO | 5.70 | 24$^*$ | 53.6 | 21120 | 4.83 | Nayak et al. (2016) |
| J72.971176-69.391112 | H72.97-69.39 | 6.30$^*$ | ... | 60.6 | 21290 | 4.53 | Carlson et al. (2012) |
| J84.906182-69.769472 | ... | 5.82 | 29$^\dagger$ | 40.01 | 22010 | 4.92 | Nayak et al. (2018) |
| J84.923542-69.769963 | ... | 5.52 | 34$^\dagger$ | 96.23 | 10960 | 5.34 | Nayak et al. (2018) |
| J85.018918-69.743288 | Papillon YSO | 5.07 | 50$^{**}$ | 22.31 | 22660 | 5.15 | Oliveira et al. (2013) |
| J16.280250-71.995194 | N76 YSO | 5.06 | ... | 22.31 | 22660 | 5.15 | Oliveira et al. (2013) |

$^a$ new luminosity estimates from this paper, see Section 3

$^b$ literature values for the source luminosity

$^\dagger$ from Chen et al. (2010)

$^*$ from Nayak et al. (2016)

$^{**}$ from Nayak et al. (2018)

luminosity calculated by fitting two grey-bodies to the mid- to far-IR photometry (excluding the near-IR JHK points).
Figure 2. SEDs of each source in our sample and the best-fitting model from Robitaille (2017). The black line is the best-fit model and the grey lines are models with $\chi^2_{\text{model}} - \chi^2_{\text{bestfit}} < 3$. Model-derived source properties are listed in Table 2.

Table 3. FIRE observations of high-mass star-forming regions in the LMC and SMC

| Target          | region       | RA        | DEC        | $K^*$ [mag] | $t_{\text{int}}$ [s] |
|-----------------|--------------|-----------|------------|-------------|----------------------|
| J84.703995-69.079110 | LMC/30 Dor  | 05:38:48.96 | -69:04:44.8 | 14.07       | 4 × 60               |
| J72.971176-69.391112 | LMC/N79     | 04:51:53.08 | -69:23:28.0 | 12.39       | 4 × 60               |
| J84.906182-69.769472 | LMC/N159    | 05:39:37.53 | -69:46:09.8 | 12.57       | 4 × 300              |
| J84.923542-69.769963 | LMC/N159    | 05:39:41.89 | -69:46:11.9 | 12.16       | 4 × 600              |
| J85.018918-69.743288 | LMC/N159    | 05:40:04.54 | -69:44:35.8 | 11.73       | 4 × 300              |
| J16.280250-71.995194 | SMC/N76     | 01:05:07.26 | -71:59:42.7 | 14.12       | 5 × 600              |

* K mags from Kato et al. (2007)

ABBA sequence in windy weather with ~ 1′′ – 2′′ seeing. Demographic information including total integration times for each target for the 6 sources targeted for near-IR spectroscopy are listed in Table 3.

Data reduction was performed using the FIREHOSE IDL pipeline. The software provides flat-fielding, sky subtraction, order tracing, object extraction, flux and wavelength calibration. For most of the spectrum, wavelength calibration was performed using a ThAr lamp. However, longward of ~ 2.27 µm, both ThAr and OH skylines are sparse, providing poor wavelength solutions for the reddest portions of the spectra. In this region, we compute the wavelength solution directly from the data. For J84.906182-69.769472, and J84.923542-69.769963 in N159 and J72.97-69.39, we use the detected H-Pfund lines while we fit to the H$_2$ lines for N76. For the YSO in 30 Dor, we used the CO (2-0) first overtone bandhead absorption. Few lines are detected at redder wavelengths, particularly in the Papillon YSO, making line identification difficult and the resulting correction to the wavelength solution less robust. We assume a systemic velocity of 262.2 km s$^{-1}$ for the LMC and 145.6 km s$^{-1}$ for the SMC (McConnachie 2012).

To measure line fluxes for each source, we fit each order of the spectrum with a model using a Levenberg-Marquardt least-squares fit (Markwardt 2009). The model spectrum consists of a polynomial to represent the continuum plus a Gaussian at the position of each line. Each order is fit separately, weighted by the 1-$\sigma$ Poisson errors computed in the FIREHOSE reduction. Many spectra are noisy. To improve the signal in these cases, we bin the data to a spectral resolution $R \approx 1200$ to improve line identification and fitting. All lines detected with $\geq 3\sigma$ are listed in Table 7.

5 SPECTRAL FEATURES

Binned and smoothed spectra are shown in Figure 3. The most prominent emission lines in each source are hydrogen recombination lines, although rarer and higher excitation species are seen in a few cases. Lines detected in each source are listed in Table 7. We briefly describe the relevant features of each object below.
5.1 30 Dor YSO

The most massive and luminous YSOs in the LMC reside in the R136 SSC at the heart of 30 Dor. The YSO we target in this program lies \( \sim 11 \) pc outside the central SSC where strong winds and turbulence from R136 impact ongoing star formation. J84.703995-69.079110, which we refer to as the 30 Dor YSO is the most massive YSO within the footprint of ALMA observations of 30 Dor (Nayak et al. 2016). This source remains embedded in its natal molecular gas, with a mass of \( \sim 24 \) M\(_{\odot}\) (derived by fitting the Robitaille et al. 2006 models to the SED, see Nayak et al. 2016).

The spectrum of the 30 Dor YSO shows a few of the brighter hydrogen recombination lines (Pa\(\beta\), Br\(\gamma\)) as well as He I emission at 2.058 \(\mu\)m. We also detect high ionization lines like \([S\ iii]\) 0.9533 \(\mu\)m in the 30 Dor YSO spectrum.

The 30 Dor YSO is the only source in the sample that shows the CO bandhead in absorption. Molecules readily form in the cooler envelopes of evolved stars, making CO bandhead absorption a useful probe of their extended atmo-
spheres (e.g., Förster Schreiber 2000; Bieging et al. 2002). In young sources, CO bandhead emission has been shown to trace circumstellar disks in some high-mass young stellar objects (e.g., Ilee et al. 2013). The CO bandhead has been seen in absorption in a few lower-mass stars, particularly those with high accretion rates (typically members of the FU Orionis class of objects, see e.g., Calvet et al. 1991; Hartmann & Kenyon 1996; Connelley & Reipurth 2018).

5.2 Super Star Cluster H72.97-69.39 in N79

H72.97-69.39 is a young SSC candidate located in the N79 region of the LMC. It is the most luminous site of star formation in the LMC, with physical characteristics that suggest it is a younger analog of the R136 SSC in the heart of 30 Dor (see Ochsendorf et al. 2017). ALMA observations of H72.97-69.39 suggest that the source is young as it is still associated with a significant amount of dense molecular gas. At the same time, the mass of ionized gas is small compared to other YSOs in the LMC, suggesting that the highest-mass sources are just beginning to ionize the surrounding gas (Ochsendorf et al. 2017). Gas kinematics suggest that two colliding filaments may have stimulated the formation of the SSC.

H72.97-69.39 has the richest near-IR spectrum with several well-detected lines from multiple species. In addition to blue continuum emission, we detect several hydrogen emission lines in the Paschen, Brackett, and Pfund series as well as multiple He i emission lines (see Table 7). Unlike most other sources in this sample, H72.97-69.39 also shows multiple [S ii] lines and [Fe ii] lines and a few H2 emission lines. A more detailed analysis of this rich spectrum will be presented in a separate paper.

5.3 YSOs in N159

N159 is one of the richest complexes of star formation in the LMC. Several H II regions trace recent star formation (Chen et al. 2010) and the CO intensity is the highest of any giant molecular cloud (GMC) in the LMC with associated H II regions (Fukui et al. 2008). Three distinct clouds trace different stages of star formation in the region. Both N159 West (N159-W) and N159 East (N159-E) contain O-type stars (Chen et al. 2010), but N159 South (N159-S) does not. Nevertheless, N159-W and N159-E have different star formation activity, suggesting that the two clouds are in different stages of their evolution. Proto-stars in N159-W appear to be younger and the majority are still found within their parental molecular gas clumps. Recent ALMA observations revealed the first extragalactic protostellar molecular outflows emanating from N159-W (Fukui et al. 2015). In contrast, N159-E has more evolved protostars which have cleared out their surrounding dust and gas (Nayak et al. 2018).

We observe three YSOs in N159 with FIRE: two in N159-W and one in N159-E. In N159-W, we observed the most massive YSO that lies within the footprint of the ALMA data (J84.906182-69.769472, see Nayak et al. 2018) as well as a YSO located at the center of two colliding filaments (J84.923542-69.769963, see Fukui et al. 2015). Both sources have masses \( \sim 30 \, M_\odot \) (derived from model fits to the SED assuming a single source dominates the luminosity, see Chen et al. 2010). In N159-E, we target a \( \sim 20 \, M_\odot \) protostar J85.018918-69.743288, also known as the Papillon YSO (Chen et al. 2010; Nayak et al. 2018). This source is located at the center of three colliding filaments, but its immediate environment is devoid of any molecular gas. We describe each source and the features in its near-IR spectrum below.

5.3.1 J84.906182-69.769472

The spectrum of J84.906182-69.769472 is dominated by hydrogen recombination lines and He i emission lines. J84.906182-69.769472 is one of three sources that shows [Fe ii] 1.64 \( \mu m \) emission. Near-IR [Fe ii] emission is often assumed to be shock excited as it is seen in protostellar jets and supernova remnants (e.g., Giammini et al. 2013; Brulsema et al. 2014). However, significant FUV radiation in H II regions may allow photoexcitation to dominate (e.g., Mouru et al. 2000). We consider source excitation conditions further in Section 6.3.

5.3.2 J84.923542-69.769963

J84.923542-69.769963 in N159-W is one of two sources associated with a bipolar molecular outflow (Fukui et al. 2015). Indeed, the J84.923542-69.769963 YSO has the youngest evolutionary classifications of sources in our sample as a YSO2 (see Table 1). Near-IR continuum emission appears to rise toward redder wavelengths, as seen in younger YSOs. Poor telluric subtraction and the low overall S/N of the binned spectrum permits the detection of only a few hydrogen recombination lines.

5.3.3 J85.018918-69.743288/ Papillon Nebula YSO

The Papillon Nebula in N159E is a compact, high-excitation H II region. Like J84.923542-69.769963, the Papillon nebula lies at the intersection of molecular filaments (Saigo et al. 2017). Chen et al. (2010) suggest that the central source, the Papillon YSO, is a cluster of multiple stars with a \( \sim 20 \, M_\odot \) source dominating the flux. In the FIRE spectrum, we detect a few hydrogen recombination lines.

5.4 N76 YSO

Our only target in the SMC is the brightest YSO in N76. Silicate absorption in the Spitzer IRS spectrum indicates that the N76 YSO remains relatively embedded (see Table 1 and Oliveira et al. 2013). However, the absence of ice absorption indicates that the protostar has begun to heat the envelope and weak PAH emission suggests the onset of UV radiation. Two pure-rotational H2 lines are detected in the IRS spectrum of the N76 YSO. Ward et al. (2017) resolved this source into two components; our pointing and K mag (see Table 3) correspond to their source 28 A which dominates the K-band emission in the region. In addition, they find extended Brγ and H2 emission, both with velocities redshifted \( \sim 5 – 10 \, km \, s^{-1} \) relative to the continuum, that suggest the presence of an outflow. Ward et al. (2017) also detected a second source \( \sim 1” \) away, 28 B. This second object has a
featureless continuum, calling into question whether or not it is a YSO.

Our FIRE spectrum of the N76 YSO shows a few emission lines, most notably He i 1.0830 μm, [Fe ii] at 1.64 μm, and Bry at 2.16 μm. Three H2 lines – H2 1-0 Q(1) at 2.4066 μm, H2 1-0 Q(2) at 2.4134 μm, and H2 1-0 Q(3) at 2.4237 μm – appear to be marginally detected out toward ~ 2.4 μm, although this identification is uncertain given the poor wavelength solution.

6 DISCUSSION

We present new near-IR spectra of 5 high-mass star-forming regions in the LMC and one in the SMC. All 6 targets have high luminosities (L* ~ 10^5 L☉), placing them well above the luminosity cutoff that Cooper et al. (2013) used to identify high-mass star-forming regions in the Galaxy in the Red MSX Source (RMS) survey (L* ~ 10^3 L☉). The FIRE spectra presented in this paper provide simultaneous coverage over ~ 0.8 – 2.5 μm. Overall, hydrogen recombination lines dominate the detected emission lines, with many sources also showing H2, He ii 1.058 μm, and [Fe ii] emission (see Table 7). We now examine how emission lines detected in most of our sources may be used to diagnose their physical properties.

6.1 Comparing Source Classifications

Emission lines detected in the near-IR spectra support the evolutionary classifications in the literature (see Section 3). In the near-IR, as in the IRS spectra, we see many hydrogen recombination lines and fine structure emission lines that are commonly detected in H ii regions (see Table 7). This is somewhat in tension with the young evolutionary status implied by model fits to the SEDs (see Section 3). However, young sources emit the bulk of their emission at longer wavelengths where large beamizes make contamination from the environment more likely, especially for distant sources like our targets in the Magellanic Clouds (at 500 μm, the Herschel beam is 36″ corresponding to 8.7 pc at the distance of the LMC).

New ALMA data obtained with ~ 1″ resolution provide a better qualitative assessment of the source evolution via indicators like remnant natal material. Molecular gas in the immediate environs of the 30 Dor YSO, HH2.97-69.39, and the two YSOs we target in N159-W suggests that these sources are younger than an object like the Papillon YSO that has largely cleared the surrounding molecular material. Both J84.92345-69.769963 in N159-W and the N76 YSO show evidence for an associated outflow (see Fukui et al. 2015 and Ward et al. 2017, respectively), consistent with these two sources having the youngest evolutionary classifications in our sample (see Table 1). For high-mass sources (M>8 M☉), the onset of ionizing radiation precedes the end of accretion (e.g., Klaassen et al. 2011, 2018). Therefore, the presence of emission lines from an emerging H ii region does not necessarily signal that accretion has finished.

Hydrogen recombination lines dominate the spectra, likely tracing emission from the associated H ii regions. Most sources also have He i emission (5/6). Hard UV photons are required to excite He i emission, hinting that high-luminosity sources may excite the line. However, there does not appear to be a luminosity threshold required for He i in Galactic high-mass YSOs (Cooper et al. 2013) and indeed He i is seen in emission around low- and intermediate-mass stars (e.g., Edwards et al. 2003, 2006; Fischer et al. 2008; Cauley & Johns-Krull 2014; Reiter et al. 2018). In H ii regions as well as low-mass pre-main-sequence stars, photoexcitation likely dominates over collisional excitation (see, Osterbrock & Ferland 2006; Kwan & Fischer 2011, respectively). Given that He i emission is seen in young, embedded sources (e.g., Covey et al. 2011; Connelley & Greene 2014) as well as more evolved regions, it is not clearly an indicator of source mass or evolutionary stage.

We detect a larger number of near-IR emission lines from sources with the H ii classification. The two sources in the LMC with the fewest lines detected also have the lowest luminosities (see Table 3). J84.923354-69.769963 has the youngest source classification of our sources in the LMC, YSO2, and is the only source with rising continuum in the near-IR spectrum. Deeper integrations would provide better signal-to-noise data, allowing for more line detections, and thus more firm conclusions about the evolutionary stages of each source.

6.2 Extinction

To estimate the extinction to each region, we use the observed Paβ/Bry line ratio. Relative extinction between the wavelengths of the two emission lines may be computed from

\[ A_{rel} = -2.5 \times \log \left( \frac{(Pa\beta/Bry)_{obs}}{(Pa\beta/Bry)_{exp}} \right) \]

where the subscripts “obs” and “exp” denote the observed and expected flux ratios, respectively. For our sample, we assume Case B recombination which indicates an intrinsic flux ratio Paβ/Bry = 5.75 ± 0.15 appropriate for 100 < n_e < 10^4 cm^-3 and 5000 < T_e < 10^5 K (Storey & Hummer 1995).

We adopt the extinction curves for the LMC and SMC derived by Gordon et al. (2003). Using values for the average extinction curve and the average RV derived for the LMC average and SMC bar samples (RV = 3.41 and RV = 2.74, respectively), we compute E(B-V). To convert the relative extinction to AV, we use

\[ \frac{A_J}{A_V} = \frac{E(J - V)}{E(B - V)} \frac{1}{RV + 1} \]

We list derived values of E(B - V) and AV values in Table 4. Studies targeting other sight lines in the LMC and SMC report different RV values (e.g., RV = 4.5±0.2 for 30 Dor from De Marchi et al. 2016). Higher RV values will increase the estimated AV. For example, extinction to the 30 Dor YSO becomes AV = 3.24 mag, compared to the AV = 2.46 mag reported in Table 4. Gordon et al. (2003) argue that their extinction curves are consistent with a continuum, reflecting the varying local impact of star formation on dust in the ISM. Given the range of star-forming conditions sampled in this and other studies, it is possible that slightly different RV values may be appropriate for different objects.

Our targets have a range of internal extinction values. Two of the most heavily extincted objects (AV ≥ 5) also have the youngest evolutionary classifications (J84.923354-69.769963 and the N76 YSO, see Table 1). Our extinc-
tinction estimate for the N76 YSO is intermediate between the values determined by Ward et al. (2017) who found $A_V = 0.81 \pm 0.35$ mag (optical) and $A_V = 19.5 \pm 9.3$ mag (K-band) using emission line ratios with the Galactic extinction curve (Cardelli et al. 1989) and an $R_V = 3.1$.

We detect both the 1.26 $\mu$m and 1.64 $\mu$m lines of [Fe ii] in two sources, the H72.97-69.39 candidate SSC and J84.906182-69.769472. These two [Fe ii] lines originate from the same upper level, so a deviation of their observed flux compared to the intrinsic value (1.49, see Smith & Hartigan 2006) provides an independent estimate of the reddening. Following the same procedure as for the hydrogen lines, we find $A_V = 3.26 \pm 1.9$ for J84.906182-69.769472, and $A_V = 6.24 \pm 2.6$ for H72.97-69.39. These estimates are somewhat higher and lower, respectively, than values derived from the hydrogen lines, likely reflecting substructure in the gas and perhaps differences in which the emission originates within that gas.

### 6.3 Excitation

#### 6.3.1 $H_2$

Many studies of giant H II regions and star-forming galaxies use wide-field, narrowband images or targeted spectroscopy to obtain diagnostic line ratios to reveal excitation conditions in the gas (e.g., Dale et al. 2004; Riffel et al. 2013; Yeh et al. 2015). For example, the $H_2$/Brγ ratio provides two lines that are close in wavelength and therefore relatively insensitive to extinction. Collisional excitation will increase the strength of the 2.12 $\mu$m $H_2$ relative to Brγ at 2.16 $\mu$m leading to higher ratios (>1) whereas in photoexcited gas, the flux of Brγ will far outweigh that of $H_2$, leading to a smaller ratio (<0.6).

We detect the $H_2$ 1-0(S1) line at 2.12 $\mu$m in 4/6 of the sources we observed with FIRE: H72.97-69.39, J84.906182-69.769472, J84.923542-69.769963, and the N76 YSO. The $H_2$/Brγ ratio is less than one for two of our LMC sources – $H_2$/Brγ ~ 0.01 ± 0.001 for H72.97-69.39, and $H_2$/Brγ ~ 0.16 ± 0.016 for J84.906182-69.769472. These small values are similar to what Yeh et al. (2015) find from a large-area imaging study of 30 Dor. Small values in both sources suggest that fluorescence dominates over shock-excitation.

We find values slightly above one in J84.923542-69.769963 ($H_2$/Brγ ~ 1.08 ± 0.09) and the N76 YSO in the SMC ($H_2$/Brγ ~ 1.33 ± 0.08). These are also the youngest sources in the sample, with an evolutionary classifications of YSO-2 (unlike the H II regions described above; see Table 1). Shocks excited by protostellar outflows from on-going star formation may contribute to the observed $H_2$ and increase the $H_2$/Brγ ratio above the value expected for pure photoexcitation. Ward et al. (2017) also find evidence for shock excitation in the N76 YSO from higher $H_2$/Brγ ratios for the stellar source (28 A; $H_2$/Brγ = 1) and the featureless continuum source (28 B; $H_2$/Brγ > 1.3) detected ~1″ away. The N76 YSO is the only source in which we detect several $H_2$ lines with $\lambda > 2 \mu$m (see Figure 3).

Detailed analysis of multiple near-IR $H_2$ lines often reveal level populations intermediate between pure photoexcitation and pure shock-excitation, revealing the complex physical conditions in these regions (e.g. Kaplan et al. 2017). Similar analyses may be possible with higher quality spectra of the N76 YSO.

#### 6.3.2 [Fe ii]

Near-IR [Fe ii] emission lines are often assumed to be collisionally-excited in shocks given their prevalence in protostellar jets and supernova remnants (e.g., Hollenbach & McKee 1989; Morel et al. 2002; Giannini et al. 2013; Bruursema et al. 2014). However, as with $H_2$, in H II regions where significant FUV radiation permeates the region, [Fe ii] may be photoexcited. Line ratios like [Fe ii] 1.64 $\mu$m / Paβ or [Fe ii] 1.64 $\mu$m / Brγ may be used to determine the dominant excitation mechanism, as the ratio will be much larger (>1) in regions where shocks play a significant role (see, e.g., Table 1 in Labrie & Pritchett 2006).

We detect [Fe ii] emission at 1.64 $\mu$m in the same 3/6 sources in our sample where we also detect $H_2$. Emission line ratios are <1 for all sources with [Fe ii] 1.64 $\mu$m / Paβ ratio of ~0.02 ± 0.0005 for H72.97-69.39, ~0.03 ± 0.004 for J84.906182-69.769472, and ~0.06 ± 0.01 for the N76 YSO. [Fe ii] 1.64 $\mu$m / Brγ ratios are similar, with ~0.11 ± 0.003 for H72.97-69.39, ~0.17 ± 0.02 for J84.906182-69.769472, and ~0.24 ± 0.01 for the N76 YSO. Photoexcitation appears to dominate in all cases, with similar ratios to those observed in the Orion Nebula (0.009 and ~0.06, respectively, inferred from the observations of Lowe et al. 1979; Mouri et al. 2000).

| Name               | $P_{\alpha}/B_{\gamma}$ | $E(B-V)$ | $A_V$ |
|--------------------|--------------------------|----------|-------|
| 30 Dor YSO         | 4.24 ± 0.41              | 0.72 ± 0.16 | 2.46 ± 0.57 |
| H72.97-69.39       | 1.56 ± 0.01              | 3.09 ± 0.05 | 10.5 ± 0.15 |
| J84.906182-69.769472 | 5.18 ± 0.23              | 0.25 ± 0.05 | 0.84 ± 0.15 |
| J84.923542-69.769963 | 1.40 ± 0.38              | 3.34 ± 0.59 | 11.4 ± 2.05 |
| Papillon YSO       | 3.20 ± 0.31              | 1.39 ± 0.16 | 4.73 ± 0.56 |
| N76 YSO            | 0.88 ± 0.65              | 4.43 ± 0.11 | 12.13 ± 0.30 |

* assuming $R_V$=3.41 and $K_V$=2.74 for the LMC and SMC, respectively.
likely contaminates our observations, leading to our higher line luminosities. Many of our targets are also likely to be unresolved clusters (e.g., the HT2.97-69.39 candidate SSC) where multiple high-mass stars contribute to the emission.

6.5 Comparison to Galactic high-mass star-forming regions

From more than 2000 sources discovered in the RMS survey, Cooper et al. (2013) selected targets classified as probable YSOs based on multi-wavelength imaging and subject to a rough luminosity cut of $L > 10^3 \, L_\odot$ corresponding to $M > 8 \, M_\odot$ (Mottram et al. 2011). Lines commonly detected in the spectra of those high-mass YSOs include Brγ, H2, fluorescent Fe ii emission at 1.68 μm, CO bandhead emission, and He i at 2.058 μm.

Our targets correspond to the high-luminosity end of the Cooper et al. (2013) sample and have higher line luminosities (see Figure 4). We detect Brγ emission in all of sources, similar to the high detection rate (75%) reported by Cooper et al. (2013). We detect He i 2.058 μm emission in most (5/6; 83%) of our sources, significantly more than the 15% found among the RMS high-mass YSOs. Half of our sources (3/6) show both H2 and [Fe ii] 1.64 μm emission, similar to the H2 detection frequency in the RMS high-mass YSO sample (56%; [Fe ii] could be separated from Brackett emission in only 11% of the RMS sample). Cooper et al. (2013) point to these lines as evidence of shock emission, likely signaling protostellar outflows. None of our [Fe ii]/Brγ ratios indicate that shocks contribute significantly to the excitation. The median H2/Brγ ratio of the Cooper et al. (2013) sample is 0.72, between the ratios computed for our sample. Given the diversity of sources in both samples, this likely reflects a range of excitation conditions with high-mass star-forming regions.

Finally, Cooper et al. (2013) report relatively high detection rates of fluorescent Fe ii emission at 1.68 μm (26%) and CO bandhead emission (17%). Stringent excitation conditions point to an origin in circumstellar disks for both emission lines. We do not detect either line in emission in any of our sources. Only one source shows the CO bandhead is seen in absorption; we consider this peculiar object in the next Section.

6.6 CO bandhead absorption: evidence for a disk?

We detect the CO bandhead in absorption in the 30 Dor YSO. Photometric classifications sometimes confuse YSOs and evolved stars since both are red and often dust-shrouded. Alone, CO bandhead absorption might suggest that the 30 Dor YSO was mistakenly identified. However, this source has a rising continuum in the IRS spectrum as well as PAH emission features and forbidden emission lines; these are significantly less likely to be detected in the spectra of evolved stars. In addition, the IRS spectrum lacks other spectral features common to evolved stars (e.g., a 30 μm feature or C2H2 emission at 13.7 μm as seen in some carbon-rich sources). The 30 Dor YSO is still associated with cold, molecular gas further indicating its youth (Nayak et al. 2016). One possible explanation for the coexistence of these spectral features is that the system is a binary, with one of the stars already evolving off of the main sequence.
assumption that it is excited in the hot ($T = 2500–5000$ K), dense ($n > 10^{15}$ cm$^{-3}$) inner disk surrounding a forming star (e.g., Carr 1989; Calvet et al. 1991; Glassgold et al. 2004; Ilee et al. 2013, 2014). For sufficiently high accretion rates, viscous heating in an optically thick disk leads to higher temperatures in the disk midplane than in surface layers, such that the CO bandhead appears in absorption (see Calvet et al. 1991). A few cases of CO bandhead absorption have been reported in the spectra of low-mass stars with high accretion rates (e.g., Connelley & Reipurth 2018). Such sources are often members of the FU Orionis class of objects–low-mass pre-main-sequence stars with sudden changes in luminosity suggesting a sudden increase in the accretion rate (Hartmann & Kenyon 1996). Few emission lines tend to be detected in the spectra of outbursting sources. This raises the intriguing possibility that the CO bandhead absorption seen in the near-IR spectrum of the 30 Dor YSO traces a disk around a high-accretion rate source in the LMC.

Detections of the CO bandhead in absorption in the spectra of higher-mass sources were reported by Cooper et al. (2013) and Ward et al. (2017). Estimated extinctions to these three sources are somewhat higher than we estimate for the 30 Dor YSO (see Table 4), ranging from $A_V = 4.3 \pm 24.4$ mag (Ward et al. 2017) to $A_V > 20$ mag (Cooper et al. 2013). Of these three sources reported in the literature, two show H$_2$ emission; none have detected hydrogen recombination line emission. In contrast, multiple emission lines are seen in the near-IR spectrum of the 30 Dor YSO, although the associated H II region almost certainly contributes to the emission.

The relationship between stellar effective temperature and mass accretion rate separating CO bandhead emission from absorption from Calvet et al. (1991) suggests that for a source with $T > 10,000$ K (we estimate $T \geq 21,000$ K for the 30 Dor YSO, see Table 2), the accretion rate has to be $>10^{-5}$ M$_\odot$ yr$^{-1}$ for the bands to be seen in absorption. However, it is unclear that models developed for disks around low-mass stars are appropriate for these high-mass sources. In particular, whether high-mass stars support optically thick, geometrically thin accretion disks remains debated, with only a few detections of truly disk-like features reported in the literature (e.g., Kraus et al. 2010, 2017). In addition, simulations suggest that self-gravity dominates angular momentum transport over viscosity (Kuiper et al. 2011), so it is unclear whether midplane heating by accretion may be invoked in high-mass sources.

CO bandhead absorption in high-mass stars may indicate accretion even if the emission does not originate in a circumstellar disk. Several models for protostellar accretion suggest significant increases in the stellar radius for high accretion rates (e.g., Palla & Stahler 1992; Hosokawa & Omukai 2009; Haemmerlé et al. 2016). This produces a short-lived phase where the young high-mass stars are very luminous ($L_\star > 10^4 L_\odot$) but cool. In this case, the bandhead absorption may be photospheric, produced in the cool outer layers surrounding the hot nucleus of the nascent massive star. Such a bloated phase will be short-lived and detection of objects in this state correspondingly rare.

7 CONCLUSIONS

We present medium resolution near-IR spectra of five high-mass YSOs in the LMC and one in the SMC. All of our objects have significant ancillary data (e.g., Spitzer IRS spectra and molecular line observations from ALMA) that strongly suggest that they are young, high-mass stars.

Every target in our sample shows multiple hydrogen recombination lines in their spectra; many also show He 1 2.058 µm. Emission lines detected in these near-IR spectra allow us to estimate the extinction and excitation in these sources. Using the ratio Pa/Bry, we estimate a range of internal extinctions, $1 \lesssim A_V \lesssim 12$ mag. Sources with the highest $A_V$ estimates tend to have the younger evolutionary classifications from other authors, indicating that they are in the early phases of formation. Half of the sources in our sample show [Fe ii] 1.64 µm emission in their spectra and 4/6 show H$_2$ 2.12 µm emission. Both lines are often assumed to trace shocks, but may be photoexcited in regions with strong UV fields, as in the H ii regions associated with most of these sources. Ratios of [Fe ii] with hydrogen recombination lines indicate that photoexcitation dominates in all three sources. However, we find $0.01 \lesssim H_2/Bry \lesssim 1.3$, suggesting that shock contribute to the excitation of 2/4 sources. Sources with the highest $H_2/Bry$ ratios also have the youngest evolutionary classifications, suggesting that sources within them are still accreting and driving outflows.

We detect CO bandhead absorption in one source, the 30 Dor YSO. The source is likely young as the IRS spectra show PAH features and fine-structure emission lines typically excited in H ii regions and ALMA observations show that the source is still associated with its natal molecular cloud. However, most detections in Galactic high-mass YSOs show the CO bandhead in emission (e.g., Cooper et al. 2013), making the origin of the CO bandhead absorption in the 30 Dor YSO somewhat mysterious.

While this study presents a limited sample of a few bright objects, it nevertheless adds to the evidence that multi-wavelength observations are essential to star formation studies in the LMC and SMC. With the upcoming launch of JWST, similar studies will be possible for larger samples with fainter (and lower-mass) sources. In the meantime, ground-based near-IR spectra like we present may be used to constrain the nature of the high-mass sources embedded and emerging from the molecular gas detected with ALMA.

ACKNOWLEDGMENTS

M.R. would like to thank Rob Simcoe. M.R. was supported by a McLaughlin Fellowship at the University of Michigan. M. Meixner and O. Nayak were supported by NSF grant AST-1312902. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 665593 awarded to the Science and Technology Facilities Council. This research has made use of NASA’s Astrophysics Data System Bibliographic Services; the arXiv preprint server operated by Cornell University; and the SIMBAD and VizieR databases hosted by the Strasbourg Astronomical Data Center.
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Table 5. Near- and mid-IR photometry of FIRE targets in the LMC and SMC

| Region   | RA [J2000] | Dec [J2000] | $J$ [mJy] | $H$ [mJy] | $K$ [mJy] | IRAC [3.6] [mJy] | IRAC [4.8] [mJy] | IRAC [5.7] [mJy] | IRAC [8.0] [mJy] |
|----------|------------|-------------|-----------|-----------|-----------|------------------|------------------|------------------|------------------|
| 30 Dor   | 84.7039    | -69.0791    | 1.57 (0.14) | 21.38 (1.37) | 21.38 (1.37) | 109.82 (8.92) | 264.89 (26.84) |                   |                   |
| H72.97-69.39 | 72.97 | -69.39 | 0.015 (0.002) | 0.019 (0.002) | 0.033 (0.003) | 70.17 (7.02) | 86.44 (8.64) | 41.37 (4.13) | 100.19 (10.019) |
| N159     | 84.9061    | -69.7694    | 0.09 (0.01) | 0.11 (0.01) | 0.36 (0.03) | 11.93 (1.20) | 23.69 (2.40) | 66.79 (6.70) | 226.50 (22.60) |
| N159     | 84.9235    | -69.7699    | 0.09 (0.01) | 3.16 (3.20) | 52.55 (5.30) | 90.90 (9.00) | 182.26 (18.00) |                   |                   |
| N159     | 85.0189    | -69.7432    | 3.63 (0.36) | 2.77 (0.28) | 2.75 (0.28) | 33.79 (0.34) | 48.87 (4.89) | 136.72 (13.67) |                   |
| N76      | 16.2803    | -71.9952    | 0.33 (0.02) | 1.50 (0.08) | 21.90 (0.37) | 55.40 (0.85) | 126.00 (1.31) | 295.00 (3.46) | 265.00 (3.60) |

* near-IR photometry from Kato et al. (2007)
Table 6. mid- and far-IR photometry of FIRE targets in the LMC and SMC

| Region   | RA [J2000] | Dec [J2000] | MIPS [24] | MIPS [70] | PACS [100] | PACS [160] | SPIRE [250] | SPIRE [350] | SPIRE [500] |
|----------|------------|-------------|-----------|-----------|------------|------------|--------------|--------------|-------------|
| 30 Dor   | 84.7039    | -69.0791    | ... (...) | ... (...) | 19450 (5076) | 27370 (2511) | 1295 (667) | 5397 (698) | 6875 (593) |
| H72.97-69.39 | 72.97 | -69.39     | 6101.67 (610.17) | 64607.18 (6460.72) | 42492.91 (4249.29) | 16696.69 (1669.67) | 6823.95 (682.39) | 2575.94 (257.59) |
| N159     | 84.9061    | -69.7694    | ... (...) | ... (...) | 32150 (5260) | 27330 (3704) | 22320 (2752) | ... (...) | ... (...) |
| N159     | 84.9235    | -69.7699    | 6911 (690) | ... (...) | ... (...) | ... (...) | ... (...) | ... (...) | ... (...) |
| N159     | 85.0189    | -69.7432    | ... (...) | ... (...) | 20450 (3802) | 18960 (2662) | 4429 (866.4) | 4446 (1238) | ... (...) |
| N76      | 16.2803    | -71.9952    | 3507 (22.8) | 10960 (67) | ... (...) | ... (...) | ... (...) | ... (...) | ... (...) |

* 22 µm emission from WISE (Wright et al. 2010)
Table 7: Near-IR lines detected in LMC high-mass star-forming regions

| Line name | $\lambda$ [\(\mu\)m] | Flux $^*$ [\(10^{-17}\) erg s$^{-1}$ cm$^{-2}$] | FWHM [Å] |
|-----------|-----------------|-----------------|---------|
| $[S\;iii]$ 0.9071 | 290.2 (13.9) | 2.1 |
| $[S\;iii]$ 0.9533 | 971.5 (49.4) | 2.1 |
| Paschen 7-3 | 1.0052 | 87.8 (5.6) | 2.0 |
| He i | 1.0834 | 153.5 (9.5) | 3.1 |
| Paschen 6-3 | 1.0942 | 129.6 (7.0) | 2.2 |
| Paschen 5-3 | 1.2822 | 169.9 (8.4) | 2.6 |
| He i | 2.0587 | 35.6 (3.7) | 4.2 |
| Brackett 7-4 | 2.1661 | 40.1 (3.3) | 4.1 |
| CO 3-1 | 2.3227 | -38.3 (-4.6) | 12.5 |
| CO 4-2 | 2.3525 | -41.2 (-5.3) | 17.2 |
| CO 5-3 | 2.3829 | -40.5 (-6.1) | 16.8 |

$^*$ Flux in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$.
| Transition          | Wavelength (Å) | Intensity (K) | Temperature (K) |
|---------------------|----------------|--------------|----------------|
| He I                | 2.1126         | 281.4 (7.5)  | 5.0            |
| He I                | 2.1138         | 71.5 (7.5)   | 5.1            |
| H2 1-0:S(1)         | 2.1218         | 59.5 (6.4)   | 4.3            |
| He I                | 2.1613         | 153.5 (5.7)  | 4.5            |
| He I                | 2.1622         | 57.7 (5.6)   | 4.8            |
| He I                | 2.1647         | 296.8 (5.8)  | 4.4            |
| Brackett 7-4        | 2.1661         | 6121.9 (24.6)| 4.3            |
| He I or [Fe III]    | 2.1817         | 97.6 (6.0)   | 4.6            |
| Pfund 29-5          | 2.3492         | 163.0 (12.5) | 8.2            |
| Pfund 28-5          | 2.3545         | 79.1 (8.6)   | 4.6            |
| Pfund 27-5          | 2.3604         | 95.2 (8.5)   | 4.9            |
| Pfund 26-5          | 2.3669         | 100.4 (10.1) | 6.3            |
| Pfund 25-5          | 2.3744         | 100.2 (9.3)  | 4.9            |
| Pfund 24-5          | 2.3828         | 147.4 (10.1) | 4.9            |
| Pfund 23-5          | 2.3925         | 142.9 (10.3) | 5.3            |
| Pfund 22-5          | 2.4036         | 161.5 (10.0) | 5.0            |
| H2 1-0:Q(1)         | 2.4066         | 142.2 (12.1) | 5.4            |

**J84.906182-69.769472 in N159**

| Transition          | Wavelength (Å) | Intensity (K) | Temperature (K) |
|---------------------|----------------|--------------|----------------|
| [S III]             | 0.9533         | 1179.8 (65.2)| 2.0            |
| Paschen 8-3         | 0.9548         | 77.8 (7.9)   | 2.0            |
| Paschen 7-3         | 1.0052         | 150.4 (6.3)  | 2.1            |
| He I                | 1.0833         | 550.0 (11.0) | 3.0            |
| Paschen 6-3         | 1.0941         | 370.4 (8.15) | 2.1            |
| [Fe II]             | 1.2570         | 69.6 (4.9)   | 2.3            |
| Paschen 5-3         | 1.2821         | 1931.7 (28.9)| 2.5            |
| O I                 | 1.3168         | 60.2 (4.5)   | 2.8            |
| Brackett 19-4       | 1.5265         | 26.1 (1.9)   | 2.9            |
| Brackett 18-4       | 1.5346         | 26.6 (2.1)   | 3.3            |
| Brackett 17-4       | 1.5443         | 34.1 (2.0)   | 3.1            |
| Brackett 16-4       | 1.5561         | 39.1 (2.7)   | 3.3            |
| Brackett 15-4       | 1.5705         | 43.6 (3.0)   | 3.5            |
| Brackett 14-4       | 1.5885         | 54.7 (4.8)   | 3.6            |
| Brackett 12-4       | 1.6411         | 75.7 (8.2)   | 7.7            |
| [Fe II]             | 1.6439         | 61.1 (8.4)   | 6.6            |
| Brackett 11-4       | 1.6811         | 188.8 (7.8)  | 3.5            |
| Brackett 10-4       | 1.7367         | 301.7 (6.6)  | 3.5            |
| He I                | 2.0587         | 531.3 (12.0) | 3.1            |
| H2 1-0:S(1)         | 2.1218         | 58.2 (5.3)   | 4.9            |
| He I                | 2.1647         | 53.0 (3.6)   | 4.2            |
| Brackett 7-4        | 2.1660         | 372.6 (15.9) | 3.1            |
| [Fe III]            | 2.2186         | 58.7 (6.3)   | 6.3            |

**J84.923542-69.769963 in N159**

| Transition          | Wavelength (Å) | Intensity (K) | Temperature (K) |
|---------------------|----------------|--------------|----------------|
| [S III]             | 0.9071         | 16.9 (1.8)   | 1.3            |
| Paschen 9-3         | 0.9230         | 44.3 (7.1)   | 34.6           |
| [S III]             | 0.9533         | 58.8 (5.9)   | 1.6            |
| Paschen 6-3         | 1.0941         | 12.0 (1.1)   | 1.2            |
| He I                | 1.0833         | 7.8 (1.4)    | 3.4            |
| Paschen 5-3         | 1.2820         | 7.5 (1.7)    | 1.4            |
| H2 1-0:S(1)         | 2.1218         | 5.6 (1.3)    | 3.9            |
| Brackett 7-4        | 2.1661         | 5.3 (0.8)    | 2.4            |

**Papillon YSO in N159**

| Transition          | Wavelength (Å) | Intensity (K) | Temperature (K) |
|---------------------|----------------|--------------|----------------|
| Paschen 10-3        | 0.9016         | 87.2 (5.8)   | 0.9            |
| [S III]             | 0.9070         | 399.7 (31.9) | 2.1            |
| [S III]             | 0.9532         | 2881.5 (3.9) | 1.0            |
| He I                | 1.0832         | 44.4 (4.2)   | 3.4            |
| Paschen 6-3         | 1.0940         | 63.7 (2.0)   | 2.5            |
| Paschen 5-3         | 1.2821         | 845.6 (72.5) | 0.9            |
| He I                | 2.0586         | 166.9 (2.9)  | 1.6            |
| Brackett 7-4        | 2.1661         | 264.3 (11.2) | 0.6            |

**N76 YSO**

| Transition          | Wavelength (Å) | Intensity (K) | Temperature (K) |
|---------------------|----------------|--------------|----------------|
| He I                | 1.0833         | 25.4 (2.4)   | 6.9            |
| Paschen 5-3         | 1.2822         | 25.2 (1.6)   | 5.1            |
| He I                | 2.0587         | 14.6 (1.0)   | 11.2           |
| H2 1-0:S(1)         | 2.1218         | 37.8 (1.8)   | 5.1            |
| Brackett 7-4        | 2.1662         | 28.5 (1.1)   | 5.7            |
| H2 2-1:S(1)?        | 2.2479         | 9.8 (1.4)    | 4.5            |
| H2 1-0:Q(1)         | 2.4066         | 89.8 (1.3)   | 5.1            |
| Species   | Transition | Wavelength (µm) | Flux Density | Flux Error |
|-----------|------------|-----------------|--------------|------------|
| $\text{H}_2$ 1-0:Q(2) | 2.4134 | 24.7 (1.4) | 5.8         |
| $\text{H}_2$ 1-0:Q(3) | 2.4237 | 41.1 (1.2) | 4.9         |

* rebinned to increase S/N
† uncertainties shown in parentheses