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NEAR INFRARED SPECTRUM OF A CLASS 0 PROTOSTAR PHOTOSPHERE

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ABSTRACT

We measure the stellar photosphere of a Class 0 protostar.

Subject headings: stars: fundamental parameters — stars: individual (S68N) — stars: low-mass – stars: statistics

1. INTRODUCTION

The method is from (Czekala et al. 2016). It is similar to (Gully-Santiago et al. 2017).

1.1. *Protostars*

1.2. *Previous studies of protostar photospheres*

1.3. *Previous studies of S68N*

2. OBSERVATIONS

The observations of S68N were carried out with NIRSPEC on the Keck telescope over 5 epochs from 2003-2014. The `NIRSPEC-7` filter provided $1.84-2.63$ μm wavelength range, with native spectral resolution of $R = 1250$ from a $0''.76$ (4 pixels) $\times$ $42''.0$ slit. The individual epochs were coadded to form a single composite spectrum of signal to noise ratio $S/N \sim 30$.

3. METHOD

Our approach involves Bayesian forward modeling of the observed spectrum under a range of different assumptions about the prostellar system. We discuss the limitations of our assumptions in the discussion section.

3.1. *Composite spectrum forward model*

We assume that stellar photosphere and warm circumstellar disk emission dominate the radiation in the near-IR band. We constructed a forward model for the observed Keck spectrum using the spectral inference framework **Starfish** from Czekala et al. (2016) with support for mixture model modifications from Gully-Santiago et al. (2017). The mixture model for S68N's Keck spectrum is:

$$S_{\rm mix} = \Omega_\star B(T_\star) + \Omega_{\rm d} B(T_{\rm d}) \tag{1}$$

where $B(T)$ is the spectral radiance as a function of temperature. The ratio of solid angles relates the relative size of the emission regions:

$$\frac{\Omega_d}{\Omega_\star} = \frac{r_d^2 d^2}{r_\star^2 d^2} = \frac{r_d^2}{r_\star^2} \tag{2}$$

approximating the circumstellar disk emission as a face-on circle. More accurate estimates for the disk emission and geometries could be obtained from rigorous radiative transfer methods (Robitaille 2017, *e.g.*). We model the protostellar spectral radiance $B(T_\star)$ with Phoenix synthetic model spectra possessing an unknown-but-low surface gravity $\log g \in [2.0, 4.0]$ in cm/s^2 and an effective temperature $T_\star \in [2700, 3600]$ K. The circumstellar disk radiance is assumed to be black body, with a temperature range $T_{\rm d} \in [1000, 1700]$ K capped by the temperature at which typical dust sublimates.

The radiated spectrum passes through an unknown amount of extinction and scattering, altering its spectral shape in an uncertain—and potentially irretrievable—way. We explored several options for characterizing the extinction towards S68N. First, instead of characterizing the spectral slope by a reddening law and extinction, A_V, we instead assumed that the overall spectral shape is approximated by a third order polynomial [2]. The polynomial coefficients lacked interpretability, and may not have adequately approximated extinction power laws, so we also experimented with an A_K and a power law slope:

$$A_\lambda / A_K = \frac{\lambda}{2.2\ \mu\text{m}}^{\alpha}$$

with $\alpha \in [-2, -1.7]$ representing the power law exponent that may depend on dust properties and degree of extinction.

We assume there is zero emission attributable to mass accretion onto the star or disk. This assumption almost certainly fails for Class 0 protostars, which are still actively accreting a large fraction of their mass. We see H_2 emission lines in the $K-$band spectrum of S68N, so some degree of accretion is likely ongoing, potentially contributing non-negligible veiling in the photospheric absorption lines. In any case, the limited spectral information available does not permit a more detailed treatment of accretion or disk gas emission as is possible with higher spectral resolution (Lee et al. 2016, *e.g.*).

3.2. *Experiments*

We tried several experiments:

4. RESULTS

4.1. *Experiment 3, Run 1*

[1] NASA Ames

[2] The polynomial is parameterized as a linear combination of Chebyshev polynomials truncated to the first 3 non-constant terms.

TABLE 1
Exeriment log

Exp. #	Run. #	Desc. -	Outcome -
1	1	Original, flawed `star_veil.py` code modeled disk radiance as a constant value with no physical interpretation	Exposed need for more physical inputs
2	1	Run with `star_BB.py` code with erroneous Ω prescription, weak priors, poor first guess	Exposed need for better priors and starting guess
2	2	Run with `star_BB.py` code with erroneous Ω prescription, strong priors (T_d fixed to ~ 1100 K), good first guess	Exposed incorrect Ω treatment
3	1	Run with `star_BB.py` code with correct absolute flux level, strong priors (T_d fixed to ~ 1100 K).	Reasonable results, weak constraints on $\log g$.
3	2	Run with `star_BB.py` code with correct absolute flux level, *weak* priors (T_d variable $\in [1000, 1700]$ K).	–
4	1	Reduced spectral range to enhance $\log g$ sensitivity	Good convergence, wide posteriors
5	1	Windowing on CO and Na I, T_d fixed to ~ 1100 K	Slightly higher $T_{\rm eff}$ and $\log g$ compared to just CO window.
6	1	Introduce A_V, with fixed ($\alpha = -2.0$) slope, $\log g > 2.0$, Chebyshev 6% peak-to-valley	Tighter T_{eff} and $\log g$ posteriors than before
7	1	A_V, with variable ($\alpha \in [-2.0, -1.7]$) slope, $\log g > 2.0$, Chebyshev 2% peak-to-valley	Tighter T_{eff} and $\log g$ posteriors due to tighter Chebyshev, α limit exceeded
8	1	A_K, with variable ($\alpha \in [-2.0, -1.7]$) slope, $\log g > 2.0$, Chebyshev 2% peak-to-valley	Re-running

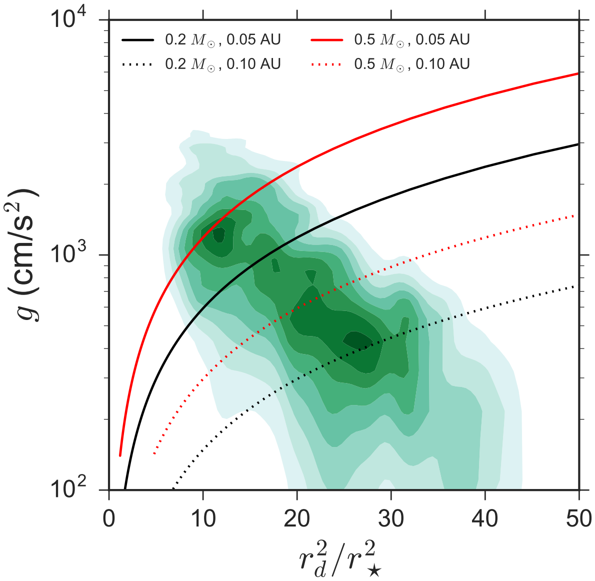

FIG. 1.— Posterior probability distribution function from Experiment 3, Run1, marginalized over all stellar and nuisance parameters except $\log g$ and $\Omega_d/\Omega_\star$. The surface gravity correlates with the solid angle ratio since both of these factors affect the CO line depths. Lines of differing stellar mass and disk radii are shown for a range of stellar radii.

5. DISCUSSION

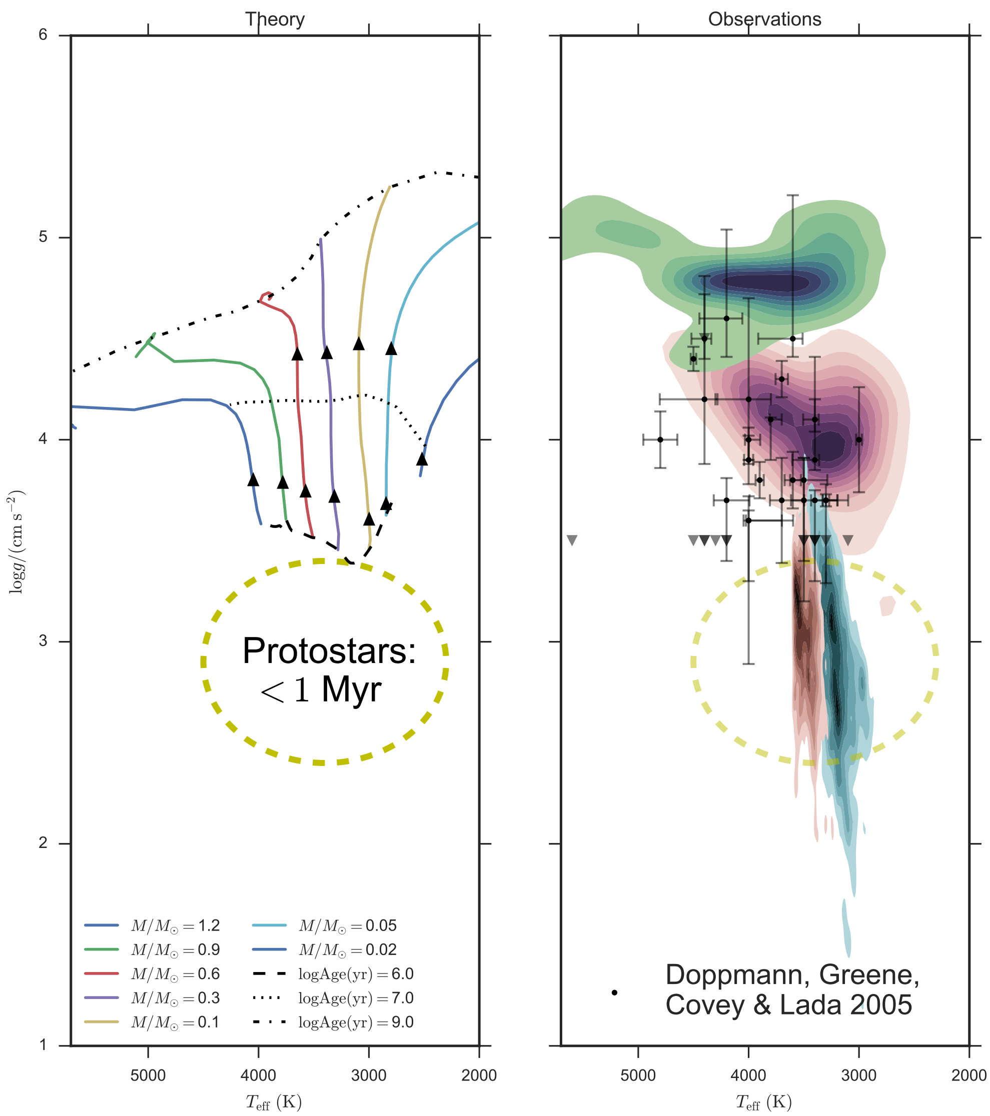

FIG. 2.— Pre-main sequence and protostar evolution comparison between theory (left panel) and obseration (right panel). The 0.02−1.2 $M_\odot$ evolutionary model tracks are from Baraffe et al. (2015), spanning 1 Myr to 100 Myr isochrones; protostars are expected to sit below the 1 Myr isochrone in the region of parameter space demarcated with a yellow dashed ellipse. The observations show coarse agreement with the models– measurements of the Pleiades from Cottaar et al. (2014, green KDE) cluster around the 100 Myr isochrone, although extend into higher-than-predicted $\log g$ for hotter stars. The younger IC348 sources (Cottaar et al. 2014, purple KDE) cluster with a large spread above and below the ~ 10 Myr isochrone. The source S 68N has a broad posterior PDF (Experiment 4-teal KDE, Experiment 3- red/brown KDE) placing its maximum a-posteriori estimate inside the range of protostars, regardless of experimental assumptions. The black dots are Class I protostars from Doppmann et al. (2005), showing a large range in measured properties with relatively large uncertainties in $\log g$.

APPENDIX

ADAPTATIONS OF STARFISH TO HANDLE ABSOLUTE FLUX AND SOLID ANGLE

We thank the Keck telescope staff.

Facilities: Keck (NIRSPEC)

Software: *pandas* (McKinney 2010), *emcee* (Foreman-Mackey et al. 2013), *matplotlib* (Hunter 2007), *numpy* (Walt et al. 2011), *scipy* (Jones et al. 2001–), *ipython* (Pérez & Granger 2007), *starfish* (Czekala et al. 2015), *seaborn* (Waskom et al. 2014)

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