Detection of Photospheric Features in the Near-infrared Spectrum of a Class 0 Protostar

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Abstract

We present a near-infrared $K$-band $R \simeq 1500$ Keck spectrum of S68N, a Class 0 protostar in the Serpens molecular cloud. The spectrum shows a very red continuum, CO absorption bands, weak or nonexistent atomic metal absorptions, and H$_2$ emission lines. The near-IR H$_2$ emission is consistent with excitation in shocks or by X-rays but not by UV radiation. We model the absorption component as a stellar photosphere plus circumstellar continuum emission with wavelength-dependent extinction. A Markov Chain Monte Carlo analysis shows that the most likely model parameters are consistent with a low-temperature, low-gravity photosphere with significant extinction and no more than modest continuum veiling. Its $T_{\text{eff}} \simeq 3260$ K effective temperature is similar to that of older, more evolved pre-main-sequence stars, but its surface gravity $\log g \simeq 2.4$ cm s$^{-2}$ is approximately 1 dex lower. This implies that the radius of this protostar is a factor of $\sim 3$ larger than that of $10^{6}$ year old T Tauri stars. Its low veiling is consistent with a circumstellar disk having intrinsic near-IR emission that is less than or equal to that of more evolved Class I protostars. Along with the high extinction, this suggests that most of the circumstellar material is in a cold envelope, as expected for a Class 0 protostar. This is the first known detection and analysis of a Class 0 protostar absorption spectrum.

Key words: circumstellar matter – stars: formation – stars: pre-main sequence – stars: protostars – techniques: spectroscopic

Supporting material: data behind figure

1. Introduction

The physical stages and observational properties of low-mass protostellar evolution have become clear over the past several decades. The IRAS, ISO, Spitzer, Herschel, and other observatories have discovered and characterized the infrared (IR) emissions of thousands of young stars embedded in nearby galactic clouds. Analysis of the IR spectral energy distributions (SEDs) and millimeter observations of the gaseous environments of these objects have shown that there are now over a hundred known low-mass Class 0 protostars in nearby (within 1 kpc) objects than have yet to accrete the majority of their final masses (see the review by Dunham et al. 2014). These are the most deeply embedded accreting objects with central gaseous cores. They have $L_{\text{sub-mm}}/L_{\text{bol}} \gtrsim 5 \times 10^{-3}$, are surrounded by massive circumstellar envelopes, and are frequently associated with jets or outflows (André et al. 1993). Much has been learned about the bolometric temperatures (Myers & Ladd 1993), luminosities, and lifetimes of the low-mass population of these young stellar objects (YSOs) from mostly unresolved far-IR space-based observations (see the review by Dunham et al. 2014). ALMA observations are now revealing high-resolution details of their envelopes and outflows (e.g., Evans et al. 2015; Aso et al. 2017).

Little is known about the heavily embedded central stars of these objects. André et al. (1993) noted that VLA 1623, the Class 0 archetype, was undetected at $\lambda < 24 \mu$m wavelengths at the time of that study. This was modeled as being due to the extremely high $A_V \gtrsim 1000$ mag extinction of its massive ($\sim 0.6 M_\odot$) circumstellar envelope. The Spitzer c2d Legacy survey detected a few dozen Class 0 YSOs (Evans et al. 2009) in nearby dark clouds, and many of them have $F_{3.6 \mu m} \gtrsim 1$ mJy (Enoch et al. 2009). We have found that some of these are detected in sensitive $K$-band ground-based observations including UKIDSS data (Lawrence et al. 2007). Some near-to-mid-IR flux is clearly leaking out through holes in the envelopes that surround these youngest stars.

Some information is known about the central stars of the somewhat more evolved Class I YSOs that are still accreting but have already accumulated the bulk of their final stellar mass. Optical and near-IR spectra have shown that these objects have late-type photospheres with effective temperatures and surface gravities similar to T Tauri stars but sometimes with considerably higher continuum veiling (or IR excess) and faster $v \sin i$ rotation velocities (see the review by White et al. 2007).

What are the natures of the central photospheres of the even more embedded Class 0 protostars? Do they have effective temperatures and surface gravities similar to those of T Tauri and Class I protostars, or are they lower gravity or otherwise different? Are they more or less veiled than the somewhat more evolved Class I population? Studying these issues would inform us of how the youngest stars assemble themselves and also probe their currently unresolved warm circumstellar disks. We have started to address these issues with a new study that has detected photospheric features in the spectrum of a Class 0 protostar for the first time.

The Class 0 source, S68N, lies in the nearby ($d = 436 \pm 9.2$ pc) Serpens star-forming cloud core (Ortiz-León et al. 2017). This region was first explored at near-IR wavelengths leading to the discovery of an embedded cluster of young stars (Strom et al. 1976; Eiroa & Casali 1992; Kaas 1999). The first
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millimeter/submillimeter continuum maps of the 6′ × 5′ Serpens core were made with the UKT14 bolometer on the JCMT,4 leading to the identification of nine distinct 1.1 mm continuum sources, some lacking NIR counterparts (Casali et al. 1993; White et al. 1995). S68N was not among these. Instead, S68N was first identified due to its strong molecular line emission (McMullin et al. 1994; Hurt et al. 1996). Subsequent special high-resolution processing of the IRAS survey data enabled construction of source SEDs leading to the identification of five distinct Class 0 protostars in the Serpens core, including S68N (Hurt & Barsony 1996). The first detection of submillimeter continuum emission from S68N was from a JCMT 450 μm map, obtained to ascertain the location of the exciting source of its compact, CS(2 → 1) outflow (Wolf-Chase et al. 1998). Enoch et al. (2009) found that S68N (also identified there as Ser-emb 8) was detected in all Spitzer IRAC (3.6–8.0 μm) and MIPS 24 and 70 μm bands with point-source fluxes ~1 mJy–10 Jy. They determined its bolometric temperature to be $T_{\text{bol}} = 58$ K when all Spitzer fluxes are combined with their 1.1 mm Caltech Submillimeter Observatory Bolocam photometry.

We describe our new near-IR spectroscopic observations of Serpens S68N and their reduction in Section 2. Next, we present our analysis of the spectrum in Section 3 and discuss its results in Section 4. Finally, we summarize our conclusions in Section 5.

2. Observations and Data Reduction

We obtained moderate resolution, moderate S/N near-IR K-band spectra of the Class 0 protostar Serpens S68N on 2014 June 18 and 19 UT with mostly clear skies and 0′.5–0′′.8 seeing. All observations were made with the Keck II telescope on Maunakea, Hawaii, using its NIRSPEC facility spectrograph (McLean et al. 1998) in its low resolution, long-slit mode.

We pointed the telescope to the band-merged Spitzer position of S68N (also identified as Ser-emb 8) given in Table 3 of Enoch et al. (2009): α = 18h29m48.1s, δ = +01°16′44″(J2000). We observed the K-band source at that location and measured the actual pointing from the telescope encoders to be within 1″ of the commanded Spitzer position in each coordinate axis. This K-band counterpart of S68N appears closest to the location of SMM 9 (T) in Figure 2 of Hodapp (1999) and has apparent magnitude $K_s = 16.1$.5

Spectra were acquired with a 0″.76 (4 pixel) wide slit, providing spectroscopic resolving power $R \equiv \lambda/\delta\lambda \approx 1000$ for PSFs larger than the slit width. The plate scale was 0″.144 pixel$^{-1}$ along the 42″ slit length. The NIRSPEC-7 blocking filter was used to record the $\lambda = 2.06$–2.46 μm wavelength range in each exposure.

The slit was held physically stationary during the exposures and thus rotated on the sky as the nonequatorially mounted telescope tracked when observing. Data were acquired in pairs of exposures of durations of 120 or 150 s each, with the telescope nodded 10″ or 15″ along the slit between integrations so that object spectra were acquired in all exposures. The A0 dwarfs HD 172792 (HIP 91748) and HD 229700 (HIP 92486) were observed for telluric correction of the protostar spectra. The telescope was automatically guided with frequent images from the NIRSPEC internal SCAM IR camera. Spectra of the internal NIRSPEC continuum lamp were taken for flat fields, and exposures of the Ne and Kr lamps were used for wavelength calibrations.

All data were reduced with IRAF. First, object and sky frames were differenced and then divided by normalized flat fields. Next, bad pixels were fixed via interpolation, and spectra were extracted with the APALL task. Spectra were wavelength calibrated using low-order fits to lines in the arc lamp exposures, and spectra at each slit position were coadded at similar airmasses and times. Instrumental and atmospheric features were removed by dividing wavelength-calibrated object spectra by spectra of the A0 dwarfs observed at similar airmasses at each slit position. Telluric-corrected spectra were produced by combining the spectra of both slit positions and then multiplying them by the spectrum of a 10,000 K dwarf stellar model. We summed the multiple individual spectra to produce a final coadded spectrum, with a total of 248.7 minutes (14,920 s) of integration time.

3. Analysis

The final spectrum of Serpens S68N is shown in Figure 1. This spectrum displays a very red continuum that is punctuated with emission and absorption features. Strong $H_2 \lambda 2.1218$, $v = 1 - 0 S(1)$, $v = 1 - 0 Q(1)$, and $v = 1 - 0 Q(3)$ emission lines are seen at 2.1218, 2.4066, and 2.4237 μm respectively. The 2.2477 μm $H_2 \lambda 2 - 1 S(1)$ line is not clearly detected. These and all wavelengths hereafter are for vacuum observations. We measured the equivalent widths and line fluxes of these features and present the results in Table 1. The measured $H_2$ FWHM line widths listed in Table 1 indicate that the emission features have widths of 194 ± 26 km s$^{-1}$. This corresponds to a resolving power of $R = 1550$ and is consistent with the quoted $R \approx 1000$ of this NIRSPEC data given that the seeing was better (less) than or equal to the slit width. Greene et al. (2010) found that Class I protostars typically have intrinsic $H_2$ FWHM line widths under 30 km s$^{-1}$, so it is not

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4 The James Clerk Maxwell Telescope is a 15 m diameter submillimeter telescope that was formerly funded by a partnership between the U.K., Canada, and the Netherlands. The East Asian Observatory took over operations in 2015 March.

5 K. Haisch (2018, private communication), from KPNO 4 m NEWFIRM photometry acquired in 2013.
The H$_2$ line is unreasonable to assume that the S68N H$_2$ lines are strongly unresolved in the spectrum.

Relatively strong $\nu v = 2$ CO absorption bands are seen over 2.29–2.39 $\mu$m wavelengths, and weak atomic absorption lines of NaI and CaI may be present in the 2.21 and 2.26 $\mu$m regions. We measured S/N $\approx 30$ at a number of continuum wavelengths across the spectrum’s $\lambda = 2.06–2.46$ $\mu$m wavelength range.

We now describe a model for the observed absorption spectrum of Serpens S68N and describe the Markov Chain Monte Carlo (MCMC) analysis we performed to estimate the most likely model parameters. We created this model to analyze the flux from the central protostar and its modification by its circumstellar environment but not the origin of the H$_2$ emission lines seen in the spectrum. We restricted the wavelengths of the analyzed spectral region to 2.1850–2.3950 $\mu$m (see Figure 1) in order to ensure that fits to the strongest photospheric absorption features would not be degraded by the relatively high noise in other regions. This region does not include any strong H$_2$ emission lines.

3.1. Spectral Modeling

We assume that the nascent photosphere of a Class 0 protostar is surrounded by a circumstellar disk and both are embedded in a large gaseous and dusty envelope within a dark cloud. We model the near-IR protostar spectrum as being the sum of contributions of components due to a stellar photosphere and excess continuum due to warm dust emission in the circumstellar disk. Wavelength-dependent extinction from the envelope and cloud is applied to both emitting components. We do not explicitly include wavelength-dependent scattering in this conceptually simple model; instead its effects are included in the extinction magnitude and its wavelength dependence. This model of the observed flux is described mathematically in Equation (1):

$$F_{\nu,\lambda} = [F_{\nu,\lambda}(T_{\rm eff}, \log g, [\text{Fe/H}]) \Omega_{*} + B_{\lambda}(T_{\text{bol}}) \Omega_{d}] 10^{-0.4A_{\nu}((\lambda/\lambda_0)^{1/2}}),$$

where $F_{\nu,\lambda}(T_{\text{eff}}, \log g, [\text{Fe/H}])$ is the flux from the protostellar photosphere of effective temperature $T_{\text{eff}}$, surface gravity log $g$, and metallicity [Fe/H]. $\Omega_{*}$ is the solid angle of the disk emission. $A_{\nu}$ is the effective $K$-band extinction with wavelength dependence $(\lambda/\lambda_0)^{1/2}$, where $\lambda_0$ is the 2.2 $\mu$m band-center wavelength. Deriving physically meaningful $\Omega_{*}$ and $\Omega_{d}$ parameters would require an absolute spectrophotometric calibration of the observed spectrum and an absolute calibration of the extinction amplitude. Such calibrations would have significant uncertainty, so hereafter we will focus on the $\Omega_{d}/\Omega_{*}$ solid angle ratio, which is effectively independent of these calibrations.

3.2. Parameter Estimation Framework

We employed the Starfish inference framework from Czekala et al. (2015) with support for mixture model modifications from Gully-Santiago et al. (2017). Starfish provides rapid parameter estimation by swift computation of the likelihood function and efficient MCMC exploration of parameter space. Rapid likelihood computation is enabled by first ingesting a pre-computed model grid and performing a principal component analysis (PCA) of the grid before starting the MCMC process. The results of this PCA are used to quickly compute model values during the information retrieval process, without having to compute complex models each time the likelihood function is evaluated. We had Starfish perform this PCA on the Husser et al. (2013) Phoenix stellar models, and then it used the PCA results to compute the photospheric flux $F_{\nu,\lambda}(T_{\text{eff}}, \log g, [\text{Fe/H}])$ in Equation (1) when evaluating the likelihood function for different model parameters. Starfish uses the emcee (Foreman-Mackey et al. 2013) package for its MCMC parameter analysis.

We augmented the physical protostar model given in Equation (1) with several other parameters that were applied to fit the spectrum of Serpens S68N but were not interpreted to have physical significance in the model (MCMC nuisance parameters). Radial velocity (RV) and spectral width terms were used to allow for slight shifts in the wavelength fit and to allow small departures from the specified instrumental resolving power. Small (~2%) residual differences between the measured absorption spectrum and the Equation (1) model were fit with a third-order Chebyshev polynomial, and three Gaussian processes parameters were also applied to allow for fitting a small amount of correlated noise.

We assigned several priors to the model parameter values before performing the MCMC analysis and we provide these in Table 2. The photospheric parameters $T_{\text{eff}}$ and log $g$ were limited to the prior ranges given in that table before the PCA was performed. We restricted [Fe/H] to the solar value in

| H$_2$ line | $\lambda$ ($\mu$m) | EW$^a$ (Å) | FWHM$^c$ (Å) | Line Flux$^d$ |
|---------|------------------|---------|-----------|---------|
| $v = 1 - 0$ S(1) | 2.1218 | $\geq 8.44$ | 15.6 | 55706 |
| $v = 2 - 1$ S(1) | 2.2477 | $\geq 0.93$ | ... | $\leq 9900^b$ |
| $v = 1 - 0$ Q(1) | 2.4066 | $\geq 6.95$ | 13.5 | 96673 |
| $v = 1 - 0$ Q(3) | 2.4237 | $\geq 7.93$ | 15.7 | 107660 |

Notes.

$^a$ Measured equivalent width from Gaussian fitting.

$^b$ Full width at half maximum of the best-fit Gaussian. All emission lines were unresolved, with FWHM <~ 20 Å as expected for the NIRSPEC $R \approx 1000$, 4 pixel wide slit.

$^c$ Line flux is the product of the EW and continuum values in instrumental units, not calibrated to physical flux units.

$^d$ The H$_2$ $v = 2 - 1$ S(1) line was not detected. 3σ upper limit values are given for EW and line flux.
order to minimize the number of model parameters, using [Fe/H] = 0.01 ± 0.001. The slight offset from [Fe/H] = 0.0 was made for computational convenience. The extinction (reddening) power-law index was limited to $\alpha = -2.0 - 1.7$ to accommodate a range of galactic extinction laws (e.g., Rieke & Lebofsky 1985; Martin & Whittet 1990; Moore et al. 2005; Nishiyama et al. 2009). Any wavelength dependence in extinction in the observed spectrum is likely a combination of true extinction and also scattering off grains (e.g., in cavity walls) into our line of sight. Thus only an effective extinction power law can be derived from the data, and scattering may be significant if there is not a good fit to the data when applying these prior values. We also limited the range of circumstellar disk temperature, and $A_K$ extinction as given in Table 2.

The RV prior was limited to ±1000 km s$^{-1}$. The spectral velocity width prior was limited to be within 240–270 km s$^{-1}$, between that of the H$_2$ lines (see the start of this section) and the quoted NIRSPEC resolving power for this mode ($R \approx 1000$ or 300 km s$^{-1}$). Using a broader prior produced broader posterior distributions of the physical model parameters, perhaps because NIRSPEC and other grating spectrographs have variable resolving power with wavelength or the impact of noise in the data. We ran Starfish for 20,000 steps, with all parameters converging to limited ranges within the first 10,000 steps.

3.3. Results

The MCMC posterior probability distributions and covariances of S68N model parameters are shown in Figure 2. Table 2 shows the derived median, 16%, and 84% (68% width) confidence values of the posterior probability distributions for the scientific model (Equation (1)) parameters of S68N and what priors were applied to the MCMC analysis. These show that the $T_{\text{eff}}$, $\log \Omega_*$, $\log \omega_*$, and $A_K$ parameters are well constrained with fairly symmetric, Gaussian-like distributions. Surface gravity is constrained to low values $\log g \lesssim 2.8$, the circumstellar disk blackbody temperature favors values $T_d \lesssim 1400$ K, and the extinction/reddening index is not strongly constrained. The spectral width parameter had a median value of 261 km s$^{-1}$ but was not well constrained.

4. Discussion

We now discuss the results of the preceding analysis and offer interpretations of the physical nature of the protostellar photosphere and its circumstellar material.

4.1. Photospheric Parameters

The most likely parameters of the S68N spectral model (Table 2) indicate that it has a low effective temperature and very low surface gravity. Its $T_{\text{eff}} \approx 3261$ K effective temperature is similar to that of a M3–M3.5 II–V star and is typical of subgiant (IV) or dwarf (V) main-sequence (PMS) stars (e.g., see Pecaut & Mamajek 2013). However, the S68N surface gravity ($\log g \approx 2.38$ cm s$^{-2}$) is much lower than that expected for a typical T Tauri star. For example, a 10$^8$ yr old, 0.20 $M_\odot$ mass, solar composition PMS star is expected to have $T_{\text{eff}} = 3226$ K and log $g = 3.39$ cm s$^{-2}$ with a radius of $R = 1.49 R_\odot$ (Baraffe et al. 2015). We estimate that the surface gravity of Serpens S68N is 1.0 dex lower, implying a radius that is $\sqrt{10}$ larger, or $R = 4.7 R_\odot$, if we assume that S68N has the same 0.20 $M_\odot$ mass of the Baraffe et al. (2015) PMS model.

This low surface gravity and large radius may be caused by internal heating due to the protostar accreting at a very high rate. Baraffe et al. (2017) showed that accretion bursts can increase the luminosities of classical T Tauri stars by over 0.5 dex compared to a nonaccreting star at the same effective temperature. It is not inconceivable that this could be on the order of 1 dex for the more heavily accreting Class 0 protostars. A 1.0 dex increase in luminosity would correspond to a $\sqrt{10}$ increase in radius, consistent with the estimated value of S68N when compared to a PMS model.

4.2. Extinction

The high extinction of S68N ($A_K = 5.82$ mag; see Table 2) corresponds to $A_V \approx 60$ mag depending on the chosen extinction law. This is consistent with the $A_V > 100$ mag extinction expected for Class 0 protostars (André et al. 1993) if its circumstellar envelope has some inhomogeneities that cause nonisotropic extinction. This may be a reasonable assumption since some near-IR flux escapes from the protostar.

We note that the near-IR flux observed from any Class 0 protostar has likely experienced both extinction and scattering by its circumstellar material (e.g., see Tobin et al. 2008). Therefore, the extinction value determined from our simple model (Equation (1)) is an effective value that is impacted by scattering. Figure 2 and Table 2 show that the MCMC analysis does not provide a very strong constraint on the effective extinction power law $\alpha$. This could be because the competing effects of extinction, scattering, and circumstellar emission are difficult to disentangle over the limited wavelength range of the spectrum.

We investigated whether the H$_2$ emission lines seen in the S68N spectrum (Figure 1) could be used as an independent measure of extinction to the protostar. The 2.4237 $\mu$m $\nu = 1 - 0$ Q(3) line and the 2.1218 $\mu$m $\nu = 1 - 0$ S(1) lines have the same upper level, so they have an intrinsic line ratio that is set by only their transition probabilities and is not a function of excitation. This would normally make this line pair an excellent extinction probe; any deviation from the intrinsic ratio $\nu = 1 - 0$ S(3)/$\nu = 1 - 0$ S(1) = 0.7 (Turner et al. 1977; Beck 2007) is expected to be due to interstellar extinction.

We measured those H$_2$ lines to have a flux ratio of 1.93 (see Table 1), consistent with extinction $A_V = 4.78$ mag. This is 1.04 mag lower than the median $A_V = 5.82$ mag estimated by our MCMC analysis (Table 2), equivalent to $\delta A_V \approx 10$ mag. The H$_2$ lines straddle the wavelengths used for fitting the protostar extinction and other parameters (2.1850–2.3950 $\mu$m; see Section 3 and Figure 1). It may be possible that extinction is lower to the emission-line region if it is located between the protostar photosphere and Earth. In that case, the emission-line extinction estimate would only be a lower limit to the total extinction to the protostar’s photosphere.

However, the H$_2$ emission-line extinction estimate is likely to be unreliable for another reason. Connelley & Greene (2010) note that there is a strong and narrow telluric absorption line in the Earth’s atmosphere at 2.42412 $\mu$m vacuum wavelength. The Earth’s orbital velocity causes this line to shift wavelength and overlap with the H$_2$ $\nu = 1 - 0$ Q(3) line, reducing its measured flux. This causes the H$_2$ emission-line extinction estimate to be underestimated here, but future space-based observations by JWST or other observatories would not have this problem.
4.3. Circumstellar Emission and Veiling

The circumstellar continuum emission in the spectrum is characterized by its effective dust temperature $T_d \simeq 1189$ K and its solid angle ratio, $\Omega_d/\Omega_\ast \simeq 3.72$ (median values in Table 2). We use these to estimate the $K$-band continuum veiling, $r_k = F_{k, CS}/F_{k, \ast}$, where $F_{k, CS}$ is the circumstellar continuum flux and $F_{k, \ast}$ is the stellar flux. We assume that both the star and the circumstellar material emit blackbody emission at their respective temperatures $T_{\text{eff}}$ and $T_d$. This approximation simplifies the continuum veiling computation to:

$$r_k \simeq \frac{B_\lambda(T_d) \Omega_d}{B_\lambda(T_{\text{eff}}) \Omega_\ast}.$$  \hspace{1cm} (2)

We evaluated this veiling equation at $\lambda = 2.2 \mu$m to estimate that the continuum veiling in the spectrum is $r_k \simeq 0.10$. This is much lower than the $r_k \sim 0.5$–3 typically found for older and less embedded Class I protostars (Doppmann et al. 2005; Connelley & Greene 2010). Furthermore, we detect $\Omega_d/\Omega_\ast$ at
only the $\sim 2\sigma$ confidence level (see Table 2), so our measured veiled value of $r_s \approx 0.10$ is highly uncertain and does not differ from $r_s = 0$ with high confidence. White et al. (2007) and Doppmann et al. (2005) found that high-resolution visible and near-IR spectra showed that Class I YSOs have effective temperatures and surface gravities similar to T Tauri PMS stars. For a given amount of warm circumstellar disk emission, $r_s$ would be expected to be about an order of magnitude lower for Class 0 protostars if their radii are about $\sqrt{10}$ times larger. Therefore, our spectrum is consistent with intrinsic warm circumstellar emission that is similar to or lower than that of Class I YSOs given the low surface gravity of S68N.

We also note that the presence of $\delta v = 2$ CO absorption bands in the spectrum is consistent with S68N not having a warm/hot, dense inner disk. Somewhat more evolved protostars have been found to sometimes have near-IR CO bands in emission (e.g., Doppmann et al. 2005; Najita et al. 2007; Connelley & Greene 2010), consistent with hot (2000–4000 K), dense ($n_H \sim 10^5$ cm$^{-3}$) circumstellar gas. Some of these have also been found to have velocity profiles consistent with rotation in circumstellar disks (e.g., Carr et al. 1993; Najita et al. 2007). Like some other Class 0 protostars (e.g., see Tobin et al. 2013), Serpens S68N may be too young to have yet developed a massive circumstellar disk, so there could be less warm material near the central photosphere than in many Class I objects. Regardless, the high extinction of S68N shows that it is surrounded by a large amount of cold material, as expected for a Class 0 protostar.

4.3.1. Nature of H$_2$ Line Emission

We now use the measured wavelengths and fluxes of the H$_2$ lines to assess the nature of this emission. We used the measured wavelengths of the H$_2$ lines to compute a mean RV of $-28.1 \pm 3.2$ km s$^{-1}$ (uncorrected to VLSR), so this emission is blueshifted by $55 \pm 13$ km s$^{-1}$ relative to the best-fit photospheric absorption line RV (Table 2). This value is 0.28 times the measured velocity width of the data and is detected at $4\sigma$ confidence. We are unsure of whether there is any useful information in this result due to its small value, and the best-fit photospheric absorption line RV may have been influenced by imperfect telluric corrections or other factors.

Finally, we assess the excitation of the circumstellar H$_2$ emission by evaluating the strengths of its observed lines. Gredel & Dalgarno (1995) showed that the ratio of H$_2$ $v = 1 - 0$ S(1) to $v = 2 - 1$ S(1) is relatively sensitive to excitation mechanisms. They computed the ratios of these two lines to be 1.9 for UV excitation, 7.7 for shocked gas at $T = 2000$ K, and 16.7 for X-ray excitation of low ionization H$_2$. Using the H$_2$ line fluxes in Table 1 and the median $\alpha = -1.83$ extinction power law from Table 2, we find that S68N’s reddening-corrected $v = 1 - 0$ S(1) to $v = 2 - 1$ S(1) line flux ratio is greater than or equal to 8.9. This value is broadly consistent with shock or X-ray but not UV excitation of H$_2$ using the Gredel & Dalgarno (1995) values above. It is difficult to distinguish between shocked and X-ray excited H$_2$ emission using only a single near-IR line ratio because collisions will thermalize the excitation levels of H$_2$ in a sufficiently dense gas (e.g., see the discussion in Greene et al. 2010). However, the measured ratio is sufficient to determine that the H$_2$ emission lines in S68N are not produced by pure UV excitation (Black & van Dishoeck 1987; Gredel & Dalgarno 1995).

5. Summary and Conclusions

We have detected weak photospheric absorption lines and H$_2$ emission lines in the near-IR, K-band spectrum of the Class 0 protostar Serpens S68N. We performed an MCMC analysis on the absorption spectrum and determined that the protostar’s photosphere has an effective temperature similar to more evolved PMS stars, but its surface gravity is on the order of 1 dex lower. This low gravity implies a large stellar radius, which may be consistent with recent and possibly episodic heavy accretion. The absorption spectrum is consistent with a large amount of effective extinction (combined extinction and scattering), as expected for a Class 0 object with a large amount of circumstellar material. Its near-IR H$_2$ emission is consistent with excitation in shocks or by X-rays but not by UV radiation. The near-IR continuum veiling is considerably lower than measured for more evolved Class I protostars and is not detected at high confidence. This is understandable given the much larger radius of the central photosphere, and it may also indicate that the there is little dust or gass mass in the inner, warm regions of the circumstellar disk. This plus the large amount of extinction suggests that most of the circumstellar material is in a cold envelope, as expected for a Class 0 protostar.

The moderate data quality of this faint object limited the precision of our analysis. We expect that JWST will produce superior quality data (higher S/N and resolving power) that will be able to constrain the properties of this and other Class 0 protostars with considerably higher precision.

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Facility: Keck:II (NIRSPEC)

Software: corner (Foreman-Mackey 2016), emcee (Foreman-Mackey et al. 2013), IRAF (Tody 1993), Starfish(Czekala et al. 2015).

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