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July, 2019

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A Radial Velocity Survey of Embedded Sources in the Rho Ophiuchi Cluster

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Received 2019 March 21; revised 2019 May 13; accepted 2019 May 24; published 2019 July 2

Abstract

We present the results of a radial velocity survey of young stellar objects (YSOs) in early stages of evolution in the core of the L1688 molecular cloud. New and archival spectra obtained with four high-resolution infrared spectrographs were analyzed using Markov chain Monte Carlo techniques that simultaneously fit for the radial velocity, T_{eff} , $v \sin i$, and veiling by comparison with synthetic spectra. The radial velocity distribution for 32 objects, most with Class I or flat-spectrum spectral energy distributions, is marginally Gaussian, with a higher dispersion relative to optical surveys at the 2σ level. When comparing the results from both proper-motion and radial velocity surveys in L1688, there is a trend for the 1D dispersions to be higher for samples of Class I/flat-spectrum YSOs that reside in the cloud core compared to Class II/III dominated samples, which are located in the lower extinction periphery. In addition, there is a velocity gradient along the major axis of the cloud core that appears more pronounced than that derived from optically visible objects at the cloud edges. If these higher dispersions for Class I/flat-spectrum objects are confirmed by future surveys, this could imply a supervirial state for the less evolved objects in the cloud core and be a signature of the initial collapse and rebound of the cluster as suggested by recent simulations of cluster evolution.

Key words: ISM: individual objects (Rho Ophiuchi Cloud) – stars: formation – stars: kinematics and dynamics – stars: pre-main sequence

1. Introduction

Simulations of cluster formation have clearly demonstrated the role of stellar encounters in their early evolution. For example, numerical simulations by Bate et al. (2003) showed the collapse and fragmentation of filaments leading to the formation of small groups of stars in dense cores. The ensuing interactions as stars emerged from these cores not only defined the evolution of the cluster’s binary fraction and velocity dispersion but also may set the initial conditions for planet formation through disruption/truncation of circumstellar disks. This picture of stars forming in collapsing self-gravitating filaments has largely been confirmed by images obtained with the *Herschel Space Observatory* (André et al. 2014). The diversity among circumstellar disks predicted through simulations (Bate 2012, 2018) is now being revealed observationally by ALMA (Cox et al. 2017; Long et al. 2018).

Surveys of dense prestellar cores in several regions of low-mass star formation have suggested that their velocity dispersions are subvirial. The Rho Ophiuchi molecular cloud, as well as its centrally condensed core L1688, has been a target for these studies owing to its proximity (137 pc) and cluster of both deeply embedded and optically visible young stellar objects (YSOs; Wilking et al. 2008; Alves de Oliveira et al. 2010; McClure et al. 2010; Ortiz-León et al. 2017). For example, André et al. (2007) used detections of N_2H^+ (1–0) emission lines toward 41 prestellar condensations and 3 protostars to derive a 1D velocity dispersion of 0.25 km s^{-1} . They estimate that the interaction times between condensations are longer than their lifetimes and do not affect dynamical interactions between newly formed stars. Consequently, one

would expect to observe a gradual increase in the velocity dispersion as YSOs emerge from their cores and interact with their neighbors.

Simple considerations of cluster relaxation timescales would suggest that velocity dispersion may indeed be a function of evolutionary state. The relaxation time for a cluster is the time it takes a cluster to approach virial equilibrium and is defined as

$$\frac{\tau_{\text{relax}}}{\tau_{\text{cross}}} = \frac{N}{6 \ln\left(\frac{N}{2}\right)}, \quad (1)$$

where N is the number of stars in the cluster. For $N > 100$, $\tau_{\text{relax}}/\tau_{\text{cross}} \approx 4$. In the case of L1688, the velocity dispersion measured from optically visible YSOs of $\sim 1 \text{ km s}^{-1}$ infers a crossing time on the order of 1.3 Myr (Rigliaco et al. 2016). Hence, τ_{relax} appears to be about 5 Myr. Estimates of the age of the cluster itself place it at about 2–3 Myr old, comparable to several crossing times (Erickson et al. 2011). The slope of the infrared spectral energy distribution (SED) of a YSO can in most cases be used as a proxy for its evolutionary state. While there are probably better discriminants for evolutionary state, such as the ratio of submillimeter to bolometric luminosity, infrared photometry has been more readily available. The spectral index of the SED, typically measured from near- to mid-infrared wavelengths, is defined as

$$\alpha = \frac{d \log(\lambda F_\lambda)}{d \log(\lambda)}, \quad (2)$$

where λ is the wavelength and F_λ is the flux density at λ . In this scheme, Class I SEDs have $1.5 > \alpha > 0.3$ and are modeled as protostar/disk/envelope systems. Flat-spectrum (FS) SEDs $0.3 > \alpha > -0.3$ and Class II SEDs $-0.3 > \alpha > -1.6$ mark the gradual dissipation of the envelope to reveal a star/disk

³ Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under contract NNH14CK55B with the National Aeronautics and Space Administration.

system such as a classical T Tauri star. Class III SEDs $\alpha < -1.6$ represent YSOs that have dissipated their disks through winds and/or planet formation and exhibit little or no excess infrared emission (Greene et al. 1994). Assuming that YSOs with Class II SEDs have average lifetimes of 2 Myr (Soderblom et al. 2014), estimates for the lifetimes of the Class I and FS classes are on average 0.5 and 0.4 Myr, respectively (Dunham et al. 2014). Consequently, the Class II and Class III objects, such as those in the Rigliaco et al. (2016) sample, have most likely been around for the entire age of the cluster and should be approaching virial equilibrium, while the Class I and FS sources have ages comparable to a crossing time and should have velocity dispersions intermediate to that of the more evolved YSOs and the dense cores.

With the goal of testing the role of stellar encounters in cluster evolution, we have conducted a radial velocity survey for a sample of mainly Class I and FS YSOs in L1688, using both new and archival data from infrared echelle spectrographs. Radial velocities were derived for 32 YSOs using Markov chain Monte Carlo (MCMC) techniques that simultaneously fit for the radial velocity, T_{eff} , $v \sin i$, and veiling by comparison with synthetic spectra with $\log g = 3.5$. The source selection, observations, and data reduction techniques are outlined in Section 2. Section 3 describes analysis of the spectra using the MCMC routine *emcee*. The derived stellar parameters are presented in Section 4, along with a detailed error analysis and an attempt to correct the radial velocity dispersion for the presence of binaries. Section 5 compares the radial velocity dispersion for this sample to the 1D dispersions derived from proper-motion studies and a radial velocity survey of more evolved objects in L1688. Possible explanations are given for the apparent higher velocity dispersion observed for less evolved sources near the cluster center in comparison to more evolved YSOs in the low-extinction periphery and may be related to the collapse or expansion of the cluster as suggested by the observed velocity gradient and recent simulations. Section 6 gives a brief summary of the results.

2. Observations and Data Reduction

Four data sets were used to derive radial velocities for a collection of YSOs in L1688, most with FS or Class I SEDs. A few Class II sources were also observed along with radial velocity standards. A summary of the YSO observations is presented in Table 1 with source positions, dates of observation, wavelength coverage, integration times, and signal-to-noise ratio (S/N) estimates. Similar data for radial velocity standards are presented in Table 2.

2.1. Source Selection

Sources were selected based on the spectral index, α , of their SEDs. The majority of our sample have Class I or FS SEDs, with some Class II objects. In addition to this, sources were selected based on their K magnitudes ($\lambda = 2.2 \mu\text{m}$) depending on the instrument and telescope used. For NIRSPEC and the Cryogenic Infrared Echelle Spectrograph (CRIRES), this resulted in sources with $K \leq 11$; for CSHELL and iSHELL, $K \leq 10$. As shown in Figure 1, the sources are concentrated within the L1688 cloud and members of subclusters corresponding to dense cores A (northwest), B (northeast), and E/F (south).

2.2. CSHELL

Observations were made using CSHELL on NASA's 3 m Infrared Telescope Facility (IRTF) on the summit of Maunakea in Hawaii. Seven first-half nights in 2016 June 23, 29, and 30 and July 10, 11, 13, and 14 were used to observe 10 YSOs and 5 radial velocity standards. Observations from June 29 and 30 were made through some cirrus cloud cover. CSHELL was an infrared echelle spectrograph with a 256 spectral by 160 spatial pixel array (Greene et al. 1993). The $1''$ wide slit was used providing a spectral resolving power of 21,500. Seven YSOs were observed at a central wavelength of $2.298 \mu\text{m}$, three at $2.2935 \mu\text{m}$, and one at both. Each setting covered a wavelength range of approximately 50 Å. The $2.298 \mu\text{m}$ setting was chosen to detect nine prominent absorption lines from the CO $v = 2-0$ band head. The $2.2935 \mu\text{m}$ setting was chosen to detect the band head itself in sources where the longer-wavelength absorption lines might be too faint to detect.

In each case, objects were nodded $15''$ along the slit in an ABBA pattern. Offset guiding was possible for most, but not all, sources. Telluric standards were taken every time the air mass had changed by approximately 0.2. Data reduction was performed using the Image Reduction and Analysis Facility (IRAF⁴). Master flats were made using dark-subtracted frames, and the data were then flat-fielded before being corrected for bad pixels. Due to the nodding, data images were subtracted in their AB pairs, and this subtraction ensured that dark current, as well as the sky background in the data images themselves, was removed. Spectra were then extracted, normalized, and divided by the telluric standards. The final step was to wavelength-calibrate the spectra using 10 telluric methane lines identified from the HITRAN database (Gordon et al. 2017).

2.3. iSHELL

Further observations were conducted using the new instrument iSHELL on NASA's 3 m IRTF the following year (Rayner et al. 2016). Three second-half nights in 2017 April 26–28 were used to observe 12 YSOs and 4 radial velocity standards, focusing on a different group of slightly fainter objects than what was possible using CSHELL. iSHELL is a $1.1\text{--}5.3 \mu\text{m}$ cross-dispersed high-resolution echelle spectrograph. For these observations a $0''.75$ slit was used, yielding a spectral resolving power of $R = 35,000$. The K2 setting was selected for each object and covered a wavelength range of $2.09\text{--}2.38 \mu\text{m}$ over 32 orders, ensuring that, once again, the CO $v = 2-0$ band head, as well as the 3–1 and 4–2 band heads, was observed, plus various atomic absorption lines.

The slit used was only $5''$ long, and therefore no nodding was done. Flats, calibration lamps, and telluric standards were observed at regular intervals. Observing efficiency was aided by guiding with an infrared slit viewing camera.

Data reduction was performed using iSHELL Tool, a program developed by Michael Cushing for the specific purpose of reducing iSHELL data based on an earlier program for a cross-dispersed spectrograph (Cushing et al. 2004). The first step in this process was to create master darks and flats. The program would then generate a wavelength calibration solution using Thorium–Argon arc lamp images that were taken as close in time to the data as possible. Following

⁴ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1
Log of YSO Observations

Source Name ^a	Other Name	R.A.(J2000) (hhmmss.s)	Decl.(J2000) (° ' ")	Date (UT)	λ_{central} (μm)	λ_{range} (μm)	Int. Time (minutes)	S/N ^b
<i>CSHELL</i>								
WLY 2-3		16 25 39.6	−24 26 34.9	2016 Jul 10	2.2980	2.2956–2.3006	16	8
VSSG 1	EL 2-20	16 26 18.9	−24 28 19.7	2016 Jul 10	2.2980	2.2956–2.3006	32	35
				2016 Jul 13	2.2935	2.2906–2.2958	36	50
SR 24N	WSB 41	16 26 58.4	−24 45 31.9	2016 Jul 14	2.2935	2.2908–2.2959	48	45
SR 24S	WSB 42	16 26 58.5	−24 45 36.9	2016 Jul 14	2.2935	2.2908–2.2959	48	55
GY 235	WLY 2-32b	16 27 13.8	−24 43 31.7	2016 Jul 14	2.2935	2.2908–2.2959	64	15
WL 20W		16 27 15.7	−24 38 43.4	2016 Jul 11	2.2980	2.2956–2.3006	60	10
WL 20E		16 27 15.9	−24 38 43.4	2016 Jul 11	2.2980	2.2956–2.3006	60	9
WLY 2-42	GY 252	16 27 21.5	−24 41 43.1	2016 Jul 11	2.2980	2.2956–2.3006	68	7
VSSG 17	WLY 2-47	16 27 30.2	−24 27 43.4	2016 Jun 23	2.2980	2.2956–2.3006	64	25
GY 314	WSB 52	16 27 39.4	−24 39 15.5	2016 Jun 23	2.2980	2.2956–2.3006	24	100
WLY 2-51	GY 315	16 27 39.8	−24 43 15.1	2016 Jul 10	2.2980	2.2956–2.3006	44	30
<i>iSHELL</i>								
VSSG 1	EL 2-20	16 26 18.9	−24 28 19.7	2017 Apr 26	2.2916	2.2835–2.2997	30	100
GY 33		16 26 27.5	−24 41 53.5	2017 Apr 28	2.2916	2.2835–2.2997	60	90
SR 24N	WSB 41	16 26 58.4	−24 45 31.9	2017 Apr 26	2.2916	2.2835–2.2997	30	180
SR 24S	WSB 42	16 26 58.5	−24 45 36.9	2017 Apr 26	2.2916	2.2835–2.2997	30	100
GY 235	WLY 2-32b	16 27 13.8	−24 43 31.7	2017 Apr 27	2.2916	2.2835–2.2997	60	50
WL 20W		16 27 15.7	−24 38 43.4	2017 Apr 27–28	2.2916	2.2835–2.2997	60	70
WL 20E		16 27 15.9	−24 38 43.4	2017 Apr 28	2.2916	2.2835–2.2997	60	50
WL 4	GY 247	16 27 18.5	−24 25 05.9	2017 Apr 27	2.2916	2.2835–2.2997	30	30
WLY 2-42	GY 252	16 27 21.5	−24 41 43.1	2017 Apr 27	2.2916	2.2835–2.2997	60	50
GY 284		16 27 30.8	−24 24 56.0	2017 Apr 27–28	2.2916	2.2835–2.2997	60	20
WLY 2-51	GY 315	16 27 39.8	−24 43 15.1	2017 Apr 26	2.2916	2.2835–2.2997	30	90
WLY 2-54	GY 378	16 27 51.8	−24 31 45.5	2017 Apr 26	2.2916	2.2835–2.2997	30	90
<i>CRIRES</i>								
GSS 26		16 26 10.3	−24 20 54.8	2008 Apr 28	2.2998	2.2949–2.3047	8	20
GY 23	GSS 32	16 26 24.0	−24 24 48.1	2008 Apr 28	2.2998	2.2949–2.3047	2	50
WL 17	GY 205	16 27 06.8	−24 38 15.0	2012 Aug 30	2.3012	2.2948–2.3075	40	30
GY 224		16 27 11.2	−24 40 46.6	2008 May 11	2.2998	2.2949–2.3047	18	50
WLY 2-44	YLW 16A	16 27 28.0	−24 39 33.5	2012 Aug 31	2.3012	2.2948–2.3075	10	65
VSSG 18	WLY 2-45	16 27 28.4	−24 27 21.0	2008 Apr 28	2.2998	2.2949–2.3047	8	35
				2012 Aug 18	2.3010	2.2960–2.3060	4	30
VSSG 17	WLY 2-47	16 27 30.2	−24 27 43.4	2012 Aug 30	2.3012	2.2948–2.3075	10	70
<i>NIRSPEC</i>								
GSS 29		16 26 16.8	−24 22 23.3	2003 Jun 21	2.2867	2.2705–2.3029	4	200
CRBR 12	ISO-Oph 21	16 26 17.2	−24 23 45.4	2003 Jun 20	2.2867	2.2705–2.3029	50	50
GY 21		16 26 23.6	−24 24 39.5	2001 Jul 10	2.2865	2.2699–2.3032	16.7	170
GY 30		16 26 25.5	−24 23 01.6	2003 Jun 19	2.2866	2.2691–2.3040	120	50
ISO-Oph 51		16 26 36.8	−24 15 51.9	2001 Jul 10	2.2865	2.2699–2.3032	15	100
GY 91		16 26 40.5	−24 27 14.5	2003 Jun 21	2.2866	2.2705–2.3028	40	55
WL 12	GY 111	16 26 44.2	−24 34 48.4	2001 Jul 7	2.2871	2.2705–2.3037	87.3	215
WL 1	GY 192	16 27 04.1	−24 28 29.9	2000 May 30	2.2846	2.2685–2.3008	30	35
GY 197		16 27 05.3	−24 36 29.8	2003 Jun 21	2.2865	2.2691–2.3040	90	20
WL 17	GY 205	16 27 06.8	−24 38 15.0	2001 Jul 10	2.2865	2.2699–2.3032	30	140
WL 10	GY 211	16 27 09.1	−24 34 08.1	2003 Jun 20	2.2866	2.2692–2.3041	20	200
GY 224		16 27 11.2	−24 40 46.6	2001 Jul 10	2.2865	2.2699–2.3032	50	150
WL 19		16 27 11.7	−24 38 32.1	2000 May 30	2.2846	2.2671–2.3022	20	150
WL 3	GY 249	16 27 19.2	−24 28 43.8	2001 Jul 10	2.2865	2.2699–2.3032	40	95
WLY 2-43	GY 265	16 27 26.9	−24 40 50.8	2001 Jul 7	2.2869	2.2706–2.3032	73.3	330
WLY 2-44	YLW 16A	16 27 28.0	−24 39 33.5	2001 Jul 8	2.2871	2.2705–2.3037	38	170
VSSG 17	WLY 2-47	16 27 30.2	−24 27 43.4	2001 Jul 10	2.2865	2.2700–2.3030	6	160
WLY 2-51	GY 315	16 27 39.8	−24 43 15.1	2003 Jun 20	2.2870	2.2705–2.3035	4	330

Notes.

^a Source names from optical studies by Struve & Rudkjøbing (1949; SR) and Wilking et al. (1987; WSB) and infrared studies by Grasdalén et al. (1973; GSS), Vrba et al. (1975; VSSG), Elias (1978; EL), Wilking & Lada (1983; WL), Young et al. (1986; YLW), Wilking et al. (1989; WLY), Greene & Young (1992; GY), Comeron et al. (1993; CRBR), and Bontemps et al. (2001; ISO-Oph).

^b Central wavelengths, wavelength ranges, and S/Ns for iSHELL are for order 226, which contains the CO $\nu = 0-2$ band head.

Table 2
Log of Radial Velocity Standards

Source Name	R.A.(J2000) (hhmmss.s)	Decl.(J2000) (° ' ")	Date (UT)	λ_{central} (μm)	λ_{range} (μm)	Sp. Ty.	RV (Pub.) ^a (km s ⁻¹)	RV (This Study) (km s ⁻¹)
<i>CSHELL</i>								
HD 111631	12 50 43.6	-00 46 05.2	2016 Jun 29	2.2980	2.2956–2.3006	M0.5 V	4.48 ± 0.15	2.5 ± 1.5
HD 122120	13 59 19.4	+22 52 11.1	2016 Jul 10	2.2980	2.2956–2.3006	K5 V	-58.04 ± 0.37	-57.1 ± 1.5
HD 147776	16 24 19.8	-13 38 30.0	2016 Jul 13	2.2935	2.2908–2.2959	K2 V	7.20 ± 0.18	5.5 ± 1.5
HD 156026	17 16 13.4	-26 32 46.1	2016 Jul 14	2.2935	2.2908–2.2959	K5 V	-0.04 ± 0.22	1.2 ± 1.5
<i>iSHELL</i>								
HD 122120	13 59 19.4	+22 52 11.1	2017 Apr 26	2.2916	2.2835–2.2997	K5 V	-58.04 ± 0.37	-56.80 ± 0.37
HD 156026	17 16 13.4	-26 32 46.1	2017 Apr 26	2.2916	2.2835–2.2997	K5 V	-0.04 ± 0.22	1.24 ± 0.37
HD 165222	18 05 07.6	-03 01 52.7	2017 Apr 27	2.2916	2.2835–2.2997	K4/5 V	32.26 ± 0.19	32.36 ± 0.37
HD 173818	18 47 27.2	-03 38 23.4	2017 Apr 28	2.2916	2.2835–2.2997	K5 V	15.33 ± 0.17	16.28 ± 0.37
<i>CRIRES</i>								
HD 129642	14 45 09.7	-49 54 58.6	2008 Apr 28	2.2998	2.2949–2.3047	K2 V	-6.47 ± 0.20	-6.28 ± 0.12
<i>NIRSPEC</i>								
GJ 806	20 45 04.1	+44 29 56.6	2003 Jun 19	2.2867	2.2705–2.3029	M2 V	-24.84 ± 0.31	-24.3 ± 1.3
HD 201091	21 06 53.9	+38 44 57.9	2003 Jun 19	2.2867	2.2705–2.3029	K5 V	-64.94 ± 0.14	-65.8 ± 1.3

Note.

^a Radial velocities from the *Gaia* DR2 data release (Soubiran et al. 2018).

Figure 1. Location of YSOs for which radial velocities were derived shown relative to the distribution of cold dust in L1688 as measured from the 1.3 mm continuum observations of Motte et al. (1998). The (0,0) position corresponds to R.A.(2000) = 16^h27^m and decl.(2000) = -24^d30'. The source symbols represent their SED class: circles—Class I; triangles—FS; diamonds—Class II. The figure is adapted from Ossenkopf et al. (2008).

identification of the apertures for spectral extraction, dark subtraction, flat-fielding, background subtraction, spectral extraction, and wavelength calibration would all be performed automatically. The next step was to apply these same steps to the telluric standards, divide out the telluric lines, and clean up any bad pixels. It should be noted that during the telluric division a small wavelength shift was applied to the telluric based on the cross-correlation of the YSO spectrum and the telluric in order to improve telluric division. This implies a small uncertainty in the wavelength calibration solution that varies for each source. The shift was always less than 0.5 pixels and was recorded for the spectrum of each source.

2.4. NIRSPEC

In addition to our own observations, high-resolution infrared spectra were generously provided from the published observations

of Doppmann et al. (2005) obtained using NIRSPEC on the 10 m Keck II telescope on Maunakea, Hawaii (McLean et al. 1998). Observations were made on 2000 May 30, 2001 July 7, 8, and 10, and 2003 June 20–21. Fifteen Class I and FS YSOs within the L1688 region were observed, usually having $K \geq 10$. The 0".58 slit was used, providing a spectral resolving power of $R = 18,000$. Several orders were obtained in the original data, but for this project, only order 33, containing the CO $v = 2-0$ band head, was analyzed. All data were reduced by Doppmann et al. using IRAF. Images were cleaned of bad pixels and cosmic rays, flat-fielded, and sky-subtracted. Extracted spectra were then wavelength-calibrated and co-added with spectra at the same slit position and similar air masses. Further details can be found in the original paper.

2.5. CRILES

Spectra for seven YSOs were reduced from the European Southern Observatory archive taken with the CRILES, which is an adaptive-optics-assisted spectrograph mounted on the 8 m VLT UT1 (Antu) located at Paranal Observatory, Chile (Kaufl et al. 2004). Data were from Viana Almeida et al. (2012) (Program ID 081.C-0395(A)), Viana Almeida (2012, unpublished data; Program ID 089.C-0539(A)), and Cottaar (2012, unpublished data; Program ID 089.C-0753(A)). CRILES is capable of delivering a spectral resolving power of up to 100,000 in the 960–5200 nm wavelength range. Light is projected onto four detectors that are each 1024×512 pixels. Viana Almeida et al. chose to cover a wavelength range of 2.2542–2.3047 μm using a 0".3 slit to achieve a resolution of 60,000. This put the CO $v = 2-0$ absorption bands on detector 4, but CO bands were placed on detectors 1 and 3 for other sets of observations. Spectra were collected in an ABBA nodding pattern, allowing a very similar reduction process to that which was used for CSHELL as described above, including wavelength calibration using telluric methane lines.

3. Data Analysis with MCMC

In order to model the data for this project, the MCMC routine *emcee* developed by Foreman-Mackey et al. (2013) was

used to fit various physical parameters of the objects observed. Synthetic spectra were obtained from the Göttingen Spectral Library based on the PHOENIX stellar atmosphere code for solar metallicity in steps of 100 K in effective temperature and 0.5 in $\log g$ (Husser et al. 2013). Synthetics were then veiled, rotated, and Doppler-shifted until they closely matched the observed spectra. The advantage of these routines is that they are very good at exploring multidimensional parameter spaces with degeneracies. They also provide well-informed distributions of posterior parameters and their uncertainties.

3.1. *emcee Applied to Individual High-resolution Spectra*

The general procedure was to read in both the data and the synthetic as (x, y) pairs and then bin the synthetic to the same wavelength range and resolution as the data. The likelihood and priors were then constructed. When using this program, however, instead of working with regular probabilities, computations were done with the log of the probabilities in order to ensure that certain values remain positive. The log of the likelihood was then given by

$$\ln[p(y|\sigma, m)] = -\frac{1}{2} \sum \left[\frac{(y_i - m_i)^2}{\sigma^2} + \ln(2\pi\sigma^2) \right], \quad (3)$$

where y_i represents a data point, m_i represents a point on the model, and σ is the value of the data point divided by the approximate S/N. The next step was to construct the priors, which was done by setting up physically reasonable ranges for each parameter informed by physical constraints and by previous estimates in the literature when possible. With this information, the log of the probability was calculated, which was then used by *emcee* when sampling the distribution. The end result was the relative probability distributions for each of the parameters being fit, as well as their 1σ uncertainties.

The four parameters being fit were the veiling, rotational velocity, radial velocity, and effective temperature. The surface gravity was chosen in advance depending on whether the object in question was a YSO ($\log g = 3.5$) or a radial velocity standard ($\log g = 4.5$). For the program to run correctly, both the synthetic and object spectra needed to be normalized and have the same resolution and number of channels. Dereddening the spectra was not necessary given the narrow wavelength range of each order. For the wavelength range covered by most of the data, the vast majority of lines being fit were CO band heads and absorption lines from the $v = 2-0$ energy level transition. Physically, the veiling is a measure of the emission from circumstellar gas and dust and is measured through the veiling coefficient, r_k :

$$F_v = \frac{F + r_k}{1 + r_k}, \quad (4)$$

where F_v is the veiled spectrum and F is the unveiled spectrum. For example, for $r_k = 1$, the absorption-line depth is half of that compared to $r_k = 0$. Due to the sensitivity of r_k to the normalization, the veiling coefficient returned by the program was only accurate to first order but important in fitting the other parameters of interest. A simple rotational broadening kernel from the PyAstronomy package called *rotBroad()* was applied to the synthetic spectra. Unlike r_k , a higher value of $v \sin i$ will result in broader and shallower absorption lines but does not change the area of the absorption lines. The key parameter for

this study being fit was the radial velocity. This was modeled as a simple fractional pixel shift, assuming that there was a linear variation in the normalized flux between each pixel. Because the shift was measured in pixels, the uncertainties in the radial velocities being measured were directly correlated with the resolution of the instrument. CRIRES and iSHELL data produced the most precise results, with NIRSPEC data being the least precise. An equation describing the modeling of these parameters is given by

$$F_{\text{model}}[i] = \text{rotBroad} \left(\frac{F_{T_{\text{avg}}, \log g}[i + dx] + r_k}{1 + r_k}, v \sin i \right), \quad (5)$$

where F_{model} is the broadened, veiled, and shifted synthetic spectrum; $F_{T_{\text{avg}}, \log g}$ is the unbroadened, unveiled, and unshifted synthetic spectrum corresponding to a certain $\log g$ and T_{eff} ; dx is the pixel shift; r_k is the veiling factor, $v \sin i$ is the rotational velocity in km s^{-1} ; and the *rotBroad()* function is a convolution determined by $v \sin i$.

As alluded to earlier, the choice was made to vary T_{eff} continuously within the program while $\log g$ was held constant. This was done by averaging together two synthetics from the library in order to estimate a synthetic with an intermediate temperature to the models. The program then used linear interpolation to create weighted averages of these synthetics to fill in the gaps in T_{eff} and better model the spectra. To estimate the uncertainties associated with assuming a standard $\log g$, separate runs were made for a range of values in T_{eff} (± 500 K) and $\log g$ (2.5–4.5 in steps of 0.5) while not letting either be a free parameter in the program. For a given source, the derived $v \sin i$ would decrease as $\log g$ increased and r_k would decrease as T_{eff} increased and CO lines weakened. However, these variations had little effect on the pixel shift and derived radial velocity, making the most important parameter from the model fits the most reliable.

3.2. *emcee Applied to Radial Velocity Data Sets with Velbin*

In addition to using *emcee* to model individual sources, it was also used to analyze the entire sample in order to derive values for the mean velocity of the cluster, the intrinsic velocity dispersion, and the binary fraction. This is necessary because single epochs of radial velocity data are likely to have their results affected by the presence of binaries. If a source with a close binary companion happens to be observed in such a way that a component of the binary orbital motion is directed toward or away from Earth, then the observed radial velocity will be offset from the source's true motion through the cluster. The overall effect is to increase the measured radial velocity dispersion of the cluster. For clusters with higher intrinsic velocity dispersions, this effect may be small; however, for clusters with dispersions smaller than a few kilometers per second, the effect can greatly increase the measured dispersion (Kouwenhoven & de Grijs 2008, 2009; Gieles et al. 2010; McConnachie & Côte 2010).

Estimates of the intrinsic velocity dispersion, after corrections for binaries, were made using the program *Velbin* (Cottaar et al. 2012) in conjunction with *emcee*. In order to use these two programs together, the following information was required: a set of N radial velocity observations ($v_{\text{obs},i}$), each with the associated uncertainties ($\sigma_{\text{obs},i}$) and mass estimates (m_i), and assumptions about the binary period, mass ratio, and eccentricity distributions. *Velbin* interprets the radial velocity

Table 3
Best-fit YSO Parameters for $\log g = 3.5$

Source Name ^a	SED Class ^b	Instr.	T_{eff} (K)	V_{helio} (km s ⁻¹)	$v \sin i$ (km s ⁻¹)	Orders
GSS 26	II	CRIRES	4400 ± 20	-7.58 ± 0.14	19.0 ± 0.1	1
GSS 29	II	NIRSPEC	4360 ± 40	-6.7 ± 1.4	36.6 ± 0.4	1
CRBR 12	I	NIRSPEC	3460 ± 20	-12.9 ± 1.5	40.5 ± 0.7	1
VSSG 1	II	iSHELL	4370 ± 300	-3.26 ± 0.64	15.0 ± 0.4	2
GY 21	FS	NIRSPEC	4340 ± 100	-7.9 ± 1.5	20.3 ± 1.0	1
GY 23	II	CRIRES	4120 ± 20	-7.81 ± 0.14	20.9 ± 0.2	1
GY 30	I	NIRSPEC	3140 ± 20	-7.5 ± 1.5	33.5 ± 1.1	1
GY 33	FS	iSHELL	4220 ± 20	-3.67 ± 0.81	13.1 ± 0.7	3 × 2
ISO-Oph 51	FS	NIRSPEC	4500 ± 180	-4.8 ± 1.9	34.8 ± 2.1	1
GY 91	I	NIRSPEC	3450 ± 20	-7.8 ± 1.4	9.6 ± 0.2	1
WL 12	I	NIRSPEC	3420 ± 140	2.3 ± 2.3	31.6 ± 2.7	1
SR 24N	II	iSHELL	3380 ± 20	0.89 ± 0.42	9.5 ± 0.8	3
SR 24S	II	iSHELL	4900 ± 80	-0.27 ± 0.61	28.5 ± 0.5	3
WL 1	FS	NIRSPEC	3420 ± 20	-25.1 ± 1.4	13.3 ± 0.4	1
GY 197	I	NIRSPEC	3220 ± 20	-7.7 ± 1.5	49.8 ± 1.1	1
WL 17	I	NIRSPEC	3360 ± 60	-3.8 ± 1.5	3.1 ± 2.9	1
		CRIRES	3120 ± 20	-3.87 ± 0.18	14.56 ± 0.08	1
WL 10	II	NIRSPEC	4580 ± 140	-7.6 ± 1.5	39.0 ± 0.9	1
GY 224	FS	NIRSPEC	4400 ± 210	-5.8 ± 1.5	9.9 ± 2.8	1
		CRIRES	5420 ± 50	-5.54 ± 0.39	23.0 ± 0.8	1
WL 19	FS	NIRSPEC	3680 ± 380	-27.4 ± 1.7	22.7 ± 1.9	1
GY 235	FS	iSHELL	3360 ± 20	-5.4 ± 1.2	12.1 ± 0.1	2
WL 20W	FS	iSHELL	3380 ± 20	-1.96 ± 0.82	25.6 ± 0.2	1
WL 20E	FS	iSHELL	4840 ± 60	0.00 ± 0.55	41.1 ± 0.3	1
WL 4	FS	iSHELL	3260 ± 20	0.33 ± 0.38	17.0 ± 0.2	1
WL 3	I	NIRSPEC	4320 ± 30	-6.9 ± 1.4	40.7 ± 0.4	1
WLY 2-42	FS	iSHELL	4420 ± 20	-5.46 ± 0.37	22.1 ± 0.2	1
WLY 2-43	I	NIRSPEC	4920 ± 190	-8.0 ± 3.2	47.0 ± 3.6	1
WLY 2-44	I	NIRSPEC	4360 ± 380	-8.3 ± 1.8	28.9 ± 1.6	1
		CRIRES	5300 ± 60	-4.37 ± 0.41	29.1 ± 0.6	1
VSSG 18	FS	CRIRES (08)	3800 ± 20	-4.85 ± 0.14	23.61 ± 0.05	1
		CRIRES (12)	4100 ± 20	-3.37 ± 0.15	22.2 ± 0.1	1
VSSG 17	FS	NIRSPEC	4160 ± 90	-6.2 ± 1.5	41.2 ± 0.5	1
		CRIRES	4040 ± 40	-5.48 ± 0.36	43.4 ± 0.5	1
GY 284	FS	iSHELL	3440 ± 20	-3.78 ± 0.71	6.1 ± 0.5	3 × 2
GY 314	II	CSHELL	3220 ± 20	-5.5 ± 1.5	16.9 ± 0.5	1
WLY 2-51	FS	NIRSPEC	4660 ± 230	-3.5 ± 2.3	42.3 ± 2.0	1

Notes.

^a Source names are the same as in Table 1.

^b Spectral energy distribution class as defined by the spectral index from 2.2 to 24 μm .

observations as being randomly drawn from a dynamical model describing the intrinsic velocity distribution, which is assumed to be Gaussian. Free parameters for the dynamical model included the mean velocity (v_{mean}) and the velocity dispersion (v_{disp}). Then, for a certain subset of stars, a velocity offset v_{bin} was added to v_{obs} based on the binary fraction (f_{bin}). The likelihood function for observing a specific radial velocity for a given star can then be written as

$$L_i(v_{\text{obs},i}) = (1 - f_{\text{bin}})L_{\text{dyn},i}(v_{\text{obs},i}) + f_{\text{bin}} \int_{-\infty}^{+\infty} L_{\text{dyn},i}(v_{\text{obs},i} - v_{\text{bin}})L_{\text{bin},i}(v_{\text{bin}})dv_{\text{bin}}. \quad (6)$$

The likelihood function for the entire sample was computed by multiplying the individual likelihood functions. Velbin then determined the log-likelihood function, which was combined with the priors to compute the probability and fed into *emcee*, which then returned relative probability distributions for how

likely the given radial velocity data set is described by v_{mean} , v_{disp} , and f_{bin} .

4. Results

In total, there were 34 different sources that have been observed for this study. Of these, 32 had detectable CO absorption lines and yielded radial velocity measurements, which are presented in Table 3. Twenty-three of the 32 are classified as either Class I or FS objects. The location of these YSOs in the L1688 cloud relative to the distribution of cold dust is shown in Figure 1. Between all the instruments and data runs, there were five sources for which radial velocities were derived for two epochs.

4.1. Measuring Radial Velocities with *emcee*

To measure the radial velocities, all of the spectra obtained were run through the MCMC routine described in Section 3. It

Figure 2. Relative probability distributions and correlations for the four fit parameters returned by *emcee* to best match the iSHELL spectrum of order 225 of object GY 33 corresponding to $T = 4260 \pm 20$ K, $v \sin i = 13.3 \pm 0.08$ km s⁻¹, $r_k = 0.29 \pm 0.02$, and $dx = -15.57 \pm 0.04$.

was found that to explore adequately the full four-dimensional parameter space (rotational velocity, veiling, radial velocity, and temperature), the program needed 100 walkers to run for 500 steps. The output for each run was then a corner plot of the positions of these walkers along their steps, resulting in relative probability distributions. The corner plots themselves show the probability distribution for each parameter separately along the diagonal, and the off-diagonal plots show correlations between each pair of parameters. Approximately the first 100 steps were excluded from the corner plots, as this was found to be the “burn-in” time for the program to settle on what it thought were the most likely values. This results in the corner plots themselves being approximately Gaussian distributions centered on the most likely values for each parameter. These center values were then determined by finding the value that was higher than 50% of the positions of the walkers and used to create a synthetic to plot over the original data to ensure that the program was returning physically meaningful results. A sample corner plot and overlay of GY 33 taken from an iSHELL

spectrum covering the CO $v = 2-0$ band head are presented in Figures 2 and 3. Parameters derived for YSOs are presented in Table 3, and radial velocities for radial velocity standards are given in Table 2.

As seen in Figure 2, the first two parameters ($v \sin i$ and r_k) correspond directly to the physical quantities of the rotational velocity and the veiling. However, dx corresponds to the shift in the spectrum measured in pixels, which is converted to the heliocentric radial velocity given the dispersion of the instrument and corrected for the Earth’s motion around the Sun given the date and time of the observation. The last parameter, T_{eff} , is a measurement of the effective surface temperature of the star, but the actual value of T_{eff} returned by the program corresponds to the weighted average of two synthetics represented by their array index, as discussed in Section 3. In case of GY 33, the T_{eff} of 5.8 corresponds to a temperature of about 4260 K. The uncertainties in the fit parameters quoted in Table 3 are from the 16th and 84th percentiles of the marginalized distributions. While the veiling of each source

Figure 3. Synthetic overlay (blue) on top of the data (orange) for the four fit parameters returned by *emcee* to best match the iSHELL spectrum of order 225 of object GY 33 corresponding to $T = 4260 \pm 20$ K, $v \sin i = 13.3 \pm 0.08$ km s⁻¹, $r_k = 0.29 \pm 0.02$, and $dx = -15.57 \pm 0.04$.

was fit, it was found to be very sensitive to the exact location of the continuum, which is often poorly constrained for these spectra, especially those with low S/Ns or high rotational velocities. For this reason the veiling parameter has been left out of the results in Table 3.

Values for T_{eff} ranged from 3100 to 5400 K with K or M spectral types, indicating that nearly all of our sources are low-mass YSOs. A large number of sources are fast rotators, with 12 of the 32 objects exhibiting values for $v \sin i > 30$ km s⁻¹. There were two NIRSPEC sources that were outliers in radial velocity: WL 1 and WL 19. We have no explanation for their large negative velocities but note that WL 1 is a known subarcsecond binary and WL 19 is suspected to be a heavily reddened Class III object behind the molecular cloud (see the Appendix). A histogram of these radial velocities with 2 km s⁻¹ bins is shown in Figure 4. A Gaussian fit to the velocities from -12 to +2 km s⁻¹ indicates a velocity dispersion of 2.66 ± 0.70 km s⁻¹. This is significantly higher than what was expected for this cluster based on previous studies. It is also clear from this figure that the distribution itself is marginally Gaussian, making the calculation of a velocity dispersion uncertain. As described in Section 3, the program Velbin was used to analyze these data and attempted to correct for the presence of binaries (see Section 4.3).

4.1.1. Error Analysis

The 1σ statistical error in the radial velocity returned by *emcee*, while related to the S/N of our spectrum, underestimates the total error of the radial velocities presented in Table 3. Since the program did not vary the surface gravity, there will be an uncertainty associated with assuming a surface gravity. To assess this, we fixed the temperature for several sources and varied $\log g$ from 2.5 to 4.5 in steps of 0.5. Variations in $\log g$ resulted in slight variations on the best-fit pixel shifts, and an error of 0.1 pixels was typical for this effect. This means that this error will be proportional to the resolution of the instrument. As discussed below, there were several other contributions to the error that were dependent on the instrument

Figure 4. Histogram of 32 sources from the L1688 cloud with the Gaussian fit of 30 sources overlaid. The two outliers between -25 and -30 km s⁻¹ have been excluded from the fit. In the case of sources observed in two epochs, the CRIRES value was adopted.

and all added in quadrature with the error from *emcee* and $\log g$, and these are reported in Table 3. The median uncertainty of the radial velocities is 0.82 km s⁻¹.

In the case of CSHELL, there was only one YSO for which a radial velocity was derived, GY 314. The largest contribution to the error appears to be from the wavelength calibration arising from small shifts between the source and the telluric standard from which the calibration was determined. This error has been estimated to be 1.5 km s⁻¹ based on comparisons between the four radial velocity standards that were observed

with CSHELL (Table 2) and radial velocities measured for those same stars by the *Gaia* DR2 survey (Soubiran et al. 2018). This is the dominant source of uncertainty for the CSHELL radial velocities.

For NIRSPEC, due to the lower spectral resolution, the error from *emcee* is larger than that from the other spectrographs. To estimate our systematic errors, radial velocity standards from NIRSPEC were used in place of the synthetics for a few sources. This allowed for a comparison of the pixel shift of a given YSO measured against the synthetics versus the standards. It was found that the average difference was 0.3 pixels, which corresponds to an uncertainty of about 1.3 km s^{-1} . This uncertainty is attributed to the wavelength calibration since the spectra were calibrated using arc lamps available on NIRSPEC that do not contain very many bright lines near the CO bands. When this is added in quadrature with the uncertainties from the program itself and $\log g$, the typical error is around 1.5 km s^{-1} . This is nearly the same error that was quoted by Covey et al. (2006) for this data set obtained by comparing their derived radial velocities to 15 spectral standards with published values.

CRIRES has the highest spectral resolution of all the spectrographs used and yielded the smallest errors on average. It is also the case that the wavelength calibration for CRIRES spectra, using well-resolved telluric lines, was the most accurate out of all the instruments. The same method as described above, using a radial velocity standard in place of a synthetic and comparing the shifts, was used with CRIRES data as well. The difference in the shifts between the two methods was found to be, on average, less than 0.1 pixels. With the high resolution of CRIRES, this only corresponds to an uncertainty of about 0.1 km s^{-1} . Consequently, the main contributors to the radial velocity errors were the error returned by *emcee* and the error due to the assumed value of $\log g$.

Finally, for the iSHELL data, the errors quoted in Table 3 are mainly due to the wavelength calibration. During the reduction process, the iSHELL tool allows the user to have the program automatically shift the telluric by a very slight amount in order to maximize the removal of telluric lines in the final spectrum. The average shift was about 0.5 pixels and was always less than 1.0 pixel. A similar shift was seen from running *emcee* with a YSO and a radial velocity standard in place of the synthetic. For several sources the CO bands were strong enough to be seen in three orders, and the results in Table 3 are weighted averages. The derived radial velocities across multiple orders, multiple air masses (e.g., GY 33), and multiple nights (e.g., GY 284) are consistent within the errors computed considering contributions from *emcee*, the wavelength calibration, and $\log g$. This, as well as the agreement between the radial velocity standards in Table 2 with their published values, suggests that no major sources of error have been neglected.

4.1.2. Comparisons with Published Data

Many of the radial velocity measurements in Table 3 do not agree with those derived from CRIRES data published by Viana Almeida et al. (2012) within their mutual uncertainties. Of the four sources retrieved from the ESO archive, only the radial velocity of GSS 26 is close to the published value. It is not clear why their results do not match up with the ones presented here, but, as a check, the one available radial velocity standard in their data was again compared with the result obtained by the *Gaia* DR2 survey. As shown in Table 2, the

result derived from *emcee* agrees very well with the *Gaia* DR2 value but not with that derived by Viana Almeida et al. (2012). The results presented here from the NIRSPEC data can also be compared to those published by Doppmann et al. (2005) and by Covey et al. (2006). Generally, the results presented here match up better with the results obtained by Covey et al. (2006) within the mutual uncertainties, although there are a few sources where this is not true. The largest discrepancy is regarding WL 12. The best explanation is that this source has a low S/N and is probably heavily veiled, leading to a very washed out and not well-defined CO $v = 2-0$ band head. This makes it difficult for the program to line up exactly where the band head should be, and with the low resolution of the instrument, these effects could lead to a large error. Overall, the radial velocity standards derived from the NIRSPEC data agree well with those from the *Gaia* DR2 data release. The only source with a derived radial velocity from CSHELL, GY 314, has been observed before by Prato (2007) and agrees well within the mutual errors.

4.1.3. Radial Velocity Variables

While most of the data here are single-epoch, there are seven sources with multi-epoch data sets. Within the stated uncertainties, GY 314, WL 17, GY 224, and VSSG 17 do not show evidence for radial velocity variability. In the case of WLY 2-44, VSSG 18, and SR 24S, there is reason to believe that these sources have subarcsecond companions. WLY 2-44 was observed by NIRSPEC in 2002 and CRIRES in 2008 and is known to have one or perhaps two subarcsecond companions (Terebey et al. 2001; Plavchan et al. 2013). The NIRSPEC data showed a radial velocity of $-8.3 \pm 1.8 \text{ km s}^{-1}$, while the CRIRES data indicated a radial velocity of $-4.37 \pm 0.41 \text{ km s}^{-1}$. For SR 24S, Rigliaco et al. (2016) measured the radial velocity in 2012 to be $-8.2 \pm 0.33 \text{ km s}^{-1}$, while the iSHELL data taken from the spring of 2017 exhibited a radial velocity of $-0.27 \pm 0.61 \text{ km s}^{-1}$. As its wide companion, SR 24N, has a known subarcsecond companion (Simon et al. 1995; Correia et al. 2006), SR 24 could be a quadruple system. Finally, VSSG 18 was observed by CRIRES in 2008 and again in 2012. In this case, the difference is small, with the 2008 data indicating a radial velocity of $-4.85 \pm 0.14 \text{ km s}^{-1}$ and the 2012 data indicating a radial velocity of $-3.37 \pm 0.15 \text{ km s}^{-1}$. The higher precision of CRIRES and thorough error analysis indicate that these measurements are outside each other's uncertainties, implying the presence of a subarcsecond companion.

4.2. Correction for Binaries

Having established the radial velocity dispersion for 30 sources within the L1688 cloud (Figure 4), the next step was to assess the broadening of the distribution due to the presence of binary companions. The program Velbin was used in order to infer the cluster's intrinsic velocity dispersion and mean velocity assuming a binary fraction (see Section 3.2). In order to use Velbin, the program required a radial velocity, a radial velocity error, and a mass estimate for each source. Masses for YSOs are difficult to estimate, especially for deeply embedded objects with large infrared excesses. Given the $\log T_{\text{eff}}$ and distance to L1688, luminosity estimates were made for lightly veiled sources by dereddening the Two Micron All Sky Survey J magnitude (Skrutskie et al. 2006) using the extinction law of Yuan et al. (2013) and intrinsic colors for main-sequence stars

Table 4
1D Velocity Dispersions of YSOs in L1688

Type of Study	No. of Sources	SED Class	Velocity Dispersion (km s^{-1})	Notes	References
Relative proper motion (R.A./decl.)	29	Class I/FS	$0.84 \pm 0.10, 0.71 \pm 0.09$	Cores A, B, E/F	(1)
Relative proper motion (R.A./decl.)	28	Class II/III	$0.88 \pm 0.08, 1.28 \pm 0.26$	Cores A, B, E/F	(1)
Absolute proper motion (R.A.)	68	all Classes	3.30 ± 0.42	Cores E/F	(2)
Absolute proper motion (decl.)	68	all Classes	2.53 ± 0.32	Cores E/F	(2)
Absolute proper motion (R.A.)	100	Class II/III	0.98 ± 0.10	all of L1688	(3)
Absolute proper motion (decl.)	100	Class II/III	1.08 ± 0.14	all of L1688	(3)
Radial velocity	47	Class II/III	1.14 ± 0.35	outskirts of L1688 $f_{\text{bin}} = 0.56$	(4)
Radial velocity	30	Class I/FS	2.66 ± 0.70	Cores A, B, E/F	(5)
Radial velocity	30	Class I/FS	$2.81^{+0.68}_{-0.64}$	Cores A, B, E/F $f_{\text{bin}} = 0.5$	(5)
Radial velocity	30	Class I/FS	$2.39^{+0.58}_{-0.49}$	Cores A, B, E/F $f_{\text{bin}} = 1$	(5)

References. (1) Wilking et al. 2015; (2) Ducourant et al. 2017; (3) Brown et al. 2018; (4) Rigliaco et al. 2016; (5) this study.

and applying a bolometric correction (Pecaut & Mamajek 2013). Mass estimates were made by comparing $\log T_{\text{eff}}$ and luminosities to several pre-main-sequence models (D’Antona & Mazzitelli 1997; Palla & Stahler 1999; Siess et al. 1999). Published mass estimates for eight objects from this study ranged from 0.2 to $1.7 M_{\odot}$, and our mass estimates agreed with these to within a factor of two (Ressler & Barsony 2001; Correia et al. 2006; Erickson et al. 2011; Rigliaco et al. 2016; Simon et al. 2017). For more heavily veiled sources, we assumed that the mass scales roughly with $\log T_{\text{eff}}$ and assigned masses of 1.5, 1.0, 0.5, or $0.2 M_{\odot}$ accordingly.

Velbin was run using a mass ratio and period distribution derived from solar-type field stars (Raghavan et al. 2010; Reggiani & Meyer 2013) and a flat eccentricity distribution. Assuming a binary fraction for Class I and FS YSOs of 0.5 (Connelley et al. 2008) yielded values for v_{mean} and v_{disp} of $-4.8 \pm 0.6 \text{ km s}^{-1}$ and $2.81^{+0.58}_{-0.49} \text{ km s}^{-1}$, respectively. To account for the possibility that the binary fraction for deeply embedded sources may be close to 1, Velbin was also run setting $f_{\text{bin}} = 1$, resulting in the largest possible correction for binaries and a $v_{\text{disp}} = 2.39^{+0.68}_{-0.64} \text{ km s}^{-1}$. These results are summarized in Table 4. Because of the large uncertainties in mass estimates, Velbin was run on the same data set, but with the masses set at constant values of 0.5, 1.0, or $1.5 M_{\odot}$. The results of these runs are not shown here, but apart from a marginally smaller dispersion for the highest mass assumed, the dispersions were virtually indistinguishable from those presented in Table 4 for this study.

4.3. Additional Information Regarding Specific Sources

Notes regarding individual sources can be found in the Appendix. While the main focus of this project was to derive precise radial velocities from the data, there is a wealth of information that can be obtained from the iSHELL spectra. Br γ emission was detected in the spectra of VSSG 1, SR 24S, GY 235, WLY 2-51, and WLY 2-54. In addition, emission from shocked molecular hydrogen at $2.12 \mu\text{m}$ was detected in SR 24S, GY 235, and WLY 2-54. Prominent features in the spectrum of WLY 2-54, and present in the spectra of 10 other YSOs, were very narrow interstellar absorption lines from the low R and P branch of the CO $v = 2-0$ transition that can in principle reveal conditions of the foreground gas. A detailed analysis of these features is beyond the scope of this paper.

5. Analysis and Discussion

The original motivation for this survey was to learn more details about the environment in which low-mass stars form. As mentioned earlier, it is common that the dense cores out of which low-mass stars are forming are in a subvirial state (Peretto et al. 2006; André et al. 2007; Kirk et al. 2010), while studies of more evolved Class II and III YSOs show signs of being near virial equilibrium (Rigliaco et al. 2016). The initial hypothesis was that the less evolved Class I and FS sources would show a velocity dispersion somewhere in between the dense cores and the more evolved sources, as they had experienced fewer stellar encounters. Instead, we have measured a radial velocity dispersion that appears higher than that of the less evolved YSOs in L1688 (Rigliaco et al. 2016) but is consistent within 2σ . In this section, the velocity dispersions of young stars in L1688 derived from radial velocity and proper-motion surveys will be discussed. These surveys are summarized in Table 4, and the relative spatial distributions of YSOs relative to the molecular gas are displayed in Figure 5. Possible explanations for the apparent discrepancies between these surveys will be discussed, including recent simulations of cluster evolution.

5.1. Limitations of the Sample and the Binary Corrections

The inability of Velbin to derive an intrinsic radial velocity dispersion for our sample that was significantly smaller than that observed could arise for several reasons. Velbin makes its calculations by assuming that the intrinsic dispersion is Gaussian in nature, and as can be seen from the histogram of velocities (Figure 4), the radial velocity distribution is only vaguely Gaussian in shape. To assess the Gaussian nature of the radial velocity distribution, we applied the Shapiro–Wilk test of normality to this sample with the two outliers between -25 and -30 km s^{-1} removed. The test yielded a p -value = 0.054, which for a significance level of $\alpha = 0.05$ means that we cannot reject the null hypothesis that the radial velocities were drawn from a normal distribution, albeit only by a small margin. It is also possible that the assumed mass and period distributions of binaries provided by Velbin for main-sequence stars do not match up with less evolved YSOs. Perhaps a greater limitation of Velbin is that it does not consider any triple- or higher-order systems, which could be common among pre-main-sequence objects. Indeed, there are a few known triple systems in this sample (e.g., WL 4, WL 20, WLY 2-44) and a possible quadruple system (SR 24). For

Figure 5. Map of the L1688 cloud with the Rho Ophiuchi cluster, with crosses showing the locations of the sources in this study (red) compared with the locations of the sources in the Rigliaco radial velocity sample (blue), the Ducourant et al. proper-motion survey (green), and the *Gaia* DR2 proper-motion sources (magenta). Contours represent the ^{13}CO column density computed from Loren (1989) assuming LTE and $T_{\text{eff}} = 25$ K and are in units of cm^{-2} with 6×10^{14} , 3×10^{15} , and 1.5×10^{16} from lowest to highest.

example, Stassun et al. (2014) found that 6 of 13 pre-main-sequence eclipsing binaries they studied were, in fact, triple systems, implying that an overall fraction of triple systems for young stars could be on the order of 0.25.

5.2. Comparisons with Proper-motion Studies

Velocity dispersions from recent proper-motion surveys in L1688, as well as the *Gaia* DR2 data release, can be compared with those derived by this study. One advantage of proper-motion studies is that the effect of binaries on the dispersion is minimized since, over decade-long baselines, any effects due to binaries would either be averaged out over several periods or be too small to have a significant impact on the measured motion. Two proper-motion surveys were conducted in the infrared and hence not biased against less evolved YSOs. Ducourant et al. (2017) observed dense cores E and F in L1688 with an astrometric K_s filter over a 0.2×0.2 area over a 9+ yr time baseline. These data were complemented with infrared images from publicly available databases that encompassed a larger area. Absolute proper motions were obtained for 68 high-probability members with an accuracy of $\sim 1.2 \text{ km s}^{-1}$; about 40% of the sample exhibited Class I or FS SEDs. Gaussian fits to these data yielded 1D velocity dispersions for these objects in R.A. and decl. of $3.3 \pm 0.4 \text{ km s}^{-1}$ and $2.9 \pm 0.3 \text{ km s}^{-1}$, respectively. The authors note that the lack of a near-infrared reference frame and the inhomogeneous distribution of stars may introduce systematic errors that are unaccounted for.

However, on face value, the 1D velocity dispersions are consistent with those from our radial velocity study.

Wilking et al. (2015) monitored four fields in three subclusters (dense cores A, B, and E/F) in the $\lambda = 2.1 \mu\text{m}$ filter over a 12 yr period. In the absence of an absolute reference frame of background stars, relative proper motions were derived for 65 YSOs with median uncertainties in R.A. and decl. of 0.39 km s^{-1} and 0.46 km s^{-1} , respectively. Assuming that each field had the same mean proper motion, 1D velocity dispersions in R.A. and decl. were found to be $0.88 \pm 0.10 \text{ km s}^{-1}$ and $0.96 \pm 0.09 \text{ km s}^{-1}$, respectively. Furthermore, the sample could be split up nearly evenly into two groups by SED class: 29 Class I and FS objects and 28 Class II/III objects. As shown in Table 4, these groups each had relative 1D velocity dispersions derived from their R.A. and decl. motions, which were also consistent with $\sim 1 \text{ km s}^{-1}$. To reconcile these results with the 1D radial velocity dispersion of this study and that of Ducourant et al. (2017), the assumption that the average proper motion in each subcluster is the same would not be correct.

One hundred sources were extracted from the *Gaia* DR2 data release covering a square degree centered on L1688 with distances in the range of $137 \pm 5 \text{ pc}$. The median uncertainties in the absolute proper motions in R.A. and decl. were 0.15 km s^{-1} and 0.10 km s^{-1} , respectively. The areal extent of the sample overlaps well with the Rigliaco et al. radial velocity survey, and as it is an optical survey, it is also heavily biased toward low-extinction Class III YSOs. Not surprisingly, the 1D velocity dispersions of $\sim 1 \text{ km s}^{-1}$ are consistent with that derived by the Rigliaco et al. survey.

5.3. Is the Velocity Dispersion a Function of Evolutionary State?

As summarized in Table 4, the results of radial velocity and *absolute* proper-motion surveys appear to show differences in the 1D velocity dispersions between samples of Class I/FS YSOs compared to Class II/III dominated samples at the 2σ level. These samples also differ depending on whether they are concentrated toward the dense molecular cores or encompass a much larger areal extent that includes the low-extinction outskirts or surface layers of L1688. Future infrared proper-motion surveys that can establish a reliable absolute frame of reference will be able to determine whether these differences are of statistical significance. Below we explore several possibilities for the apparent higher velocity dispersions of less evolved YSOs.

5.3.1. Underestimating the Binary Fraction

It has been established that the binary fraction of YSOs is higher than that of main-sequence stars (see Reipurth et al. 2014 and references therein). For example, Rigliaco et al. (2016) derived a binary fraction of $f_{\text{bin}} = 0.56$ for their sample using *Velbin*. It is estimated that about two-thirds of Class 0 protostars are multistar systems and that this multiplicity frequency slowly drops off as the objects evolve toward the main sequence (Reipurth et al. 2014). However, due to the difficulty in resolving very close protobinaries, it is possible that the fraction is nearly 1. It is not unreasonable to think that the binary fraction could be significantly higher in samples of Class I/FS YSOs compared to those dominated by Class II/III and this would increase the observed radial velocity dispersion.

It is unlikely, however, that a higher binary fraction would explain the higher dispersion in proper-motion surveys of Class I/FS YSOs, as the binary fraction is not expected to impact the velocity dispersion significantly over decade-long time baselines.

5.3.2. Supervirial State

It is also possible that the observed velocity dispersion is pointing toward a supervirial state for the cluster. It has been estimated that for this cluster to be in virial equilibrium, the velocity dispersion should be $1.2 \pm 0.2 \text{ km s}^{-1}$ toward the dense cores and closer to 1.0 km s^{-1} for the L1688 cloud as a whole (e.g., Wilking et al. 2015). Assuming that there are not unaccounted-for effects artificially increasing the measured dispersion, these data suggest a picture whereby these YSOs form from subvirial cores, quickly become supervirial during the Class I/FS phase, and settle back down into a virial state as they continue to evolve. Past simulations have shown that during the first crossing time of a cluster, it could become slightly supervirial as the objects begin to fall toward the center (Proszkow & Adams 2009). Indeed, more recent studies and simulations have shown that these effects may be greater than first thought. Kuhn et al. (2019) and Sills et al. (2018) have shown through simulations that it is possible that clusters start to collapse very quickly after they begin to form stars. According to these simulations, by the time a cluster is 3 Myr old it has collapsed and rebounded, greatly changing the velocity dispersion as it undergoes this process. The dispersion can start out relatively small, then increase rapidly until peaking after about 2 Myr, before decreasing nearly as quickly over the next 1 Myr, until finally settling into a nearly virialized state. In addition to this, they were able to show that the velocity dispersion is the greatest toward the center of the cluster and smaller at the periphery. This scenario is broadly in agreement with the results found by this study and Ducourant et al. (2017) when compared to those of Rigliaco et al. (2016) and the *Gaia* DR2 sources. The velocity dispersion appears higher for the Class I/FS objects, which are expected to be intermediate in age between the subvirial cores and the more evolved Class II/III objects. Moreover, YSOs with the highest velocity dispersion appear to be concentrated toward the cluster center.

It should also be noted that Rigliaco et al. (2016) measured a velocity gradient in their sample corresponding to increasing velocities from the northwest toward the southeast of the cluster. This gradient was calculated to be about $1 \text{ km s}^{-1} \text{ pc}^{-1}$. This gradient is not attributed to the rotation of the cluster but is thought to be a real gradient such that the northwest section of the cluster is blueshifted relative to the southeast section. To check this for the sample presented here, the YSOs can be roughly split up into subgroups of 8 sources that lie in the northwest quadrant of Figure 1, 15 that lie in the southeast quadrant, and 5 that lie in the northeast. The average radial velocity in the northwest quadrant is $v_{\text{avg,NW}} = -7.4 \pm 2.6 \text{ km s}^{-1}$, the average velocity for the southeast quadrant is $v_{\text{avg,SE}} = -3.6 \pm 3.3 \text{ km s}^{-1}$, and the average velocity for the northeast quadrant is $v_{\text{avg,NE}} = -4.3 \pm 2.8 \text{ km s}^{-1}$. The projected separation of the northwest and southeast subgroups is about 1 pc. Certainly these samples are much smaller, but there appears to be a trend of increasing velocities toward the southeast. This would suggest that the velocity gradient of this

sample is potentially larger than the gradient of the Rigliaco et al. (2016) sample, but roughly in the same direction. According to the simulations of Proszkow & Adams (2009), a real velocity gradient will only be observed when there is either collapse or expansion happening in a nonspherical cluster that is tilted at some angle relative to the observer. It is clear from the shape of the L1688 cloud that the cluster is elongated in roughly the same direction as the velocity gradient measured by Rigliaco et al. (2016). This could indicate that L1688 may be on either side of a collapse-and-rebound process during the first 2–3 Myr of its formation.

While these simulations generally agree with the results, we note that the main difference between the simulations by Kuhn et al. (2019) and Sills et al. (2018) and the Rho Ophiuchi cloud complex is the number of cluster members. Kuhn and Sills ran simulations for clusters that consist of thousands of stars, while Rho Ophiuchi only has $\gtrsim 300$ members. With fewer members and less total mass involved, the collapse-and-rebound process may not be as pronounced as it is in larger clusters.

6. Summary

Using both new and archival data from infrared echelle spectrographs, we have conducted a radial velocity survey of YSOs in early stages of evolution in the L1688 cloud core. Radial velocities were derived for 32 YSOs using MCMC techniques that simultaneously fit for the radial velocity, T_{eff} , $v \sin i$, and veiling by comparison with synthetic spectra with $\log g = 3.5$. Values for T_{eff} indicate that all of our sources have K or M spectral types and are low-mass YSOs. Many are fast rotators, with 12 objects exhibiting values for $v \sin i > 30 \text{ km s}^{-1}$. Our radial velocities agree well with published data, except we have found discrepancies with the CRIRES data reported by Viana Almeida et al. (2012). Our data include three radial velocity variables with probable subarcsecond companions: VSSG 18, SR 24S, and WLY 2-44, with the latter source known to have such a companion. This sample displays a radial velocity distribution that is marginally Gaussian, with a higher dispersion relative to optical surveys at the 2σ level. This is counter to our expectations that the velocity dispersion would gradually increase over time once stars emerged from subvirial cores and began to interact with other cluster members.

The radial velocity dispersion of this sample has been compared to other radial velocity and absolute proper-motion surveys in L1688. There is a trend for 1D velocity dispersions to be higher for samples of Class I/FS YSOs, which reside in the cloud core, compared to Class II/III dominated samples, which are mainly located in the lower-extinction periphery. In addition, there is a velocity gradient along the major axis of the cloud core that appears more pronounced than that derived from YSOs at the cloud edges. If this is confirmed by future surveys, the supervirial state of the less evolved objects in the cloud core and the velocity gradient suggests that we are witnessing the initial collapse and rebound of the cluster in the first few million years of its existence. Such a scenario has been proposed by recent simulations of cluster evolution that also predict that the dispersion of older, more evolved YSOs should converge to virial equilibrium.

We are grateful to Michael Connelley and Michael Cushing for assistance with the CSHELL and iSHELL observations and

reduction. We also thank Greg Doppman for making the NIRSPEC data available and to Elisabetta Rigliaco for assistance with Velbin and helpful discussions on the data analysis. T.S. acknowledges support from a graduate fellowship through the NASA/Missouri Space Grant Consortium. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

Software: emcee (Foreman-Mackey et al. 2013), IRAF (Tody 1986, 1993), Velbin (Cottaar et al. 2012, as developed on GitHub).

Appendix Notes on Individual Sources

1. GSS 26. Our radial velocity of $-7.58 \pm 0.14 \text{ km s}^{-1}$, derived from a reanalysis of 2008 August CRIRES data obtained by Viana Almeida et al. (2012), is more negative than their published value of $-6.95 \pm 0.03 \text{ km s}^{-1}$. A dynamical mass of $1.5 M_{\odot}$ and a radial velocity of -6.44 km s^{-1} have been derived based on observations of its disk (Simon et al. 2017). Our derived temperature, suggesting a K5 spectral type with low veiling, is counter to previous estimates but consistent with its observed variability in veiling and brightness (Luhman & Rieke 1999; Greene & Lada 2000).
2. VSSG 1. Our best-fit temperature of 4430 K suggests a mid-K spectral type. In addition to the photospheric absorption lines, the iSHELL spectrum shows Brackett gamma in emission.
3. GY 21. Best-fit temperature is warmer and $v \sin i$ smaller than derived from the CSHELL spectrum of Greene & Lada (1997) but in better agreement with those derived from the same spectrum by Doppmann et al. (2005).
4. GY 23/Source 2. Spectral classifications vary from K5 to M0 (Greene & Lada 1997; Luhman & Rieke 1999; Doppmann et al. 2005; Erickson et al. 2011). Temperature and $v \sin i$ are in good agreement with Greene & Lada (1997). Our best-fit temperature and low veiling favor the mid-K classification of Erickson et al. (2011). Our modeling of the 2008 April CRIRES spectrum obtained by Viana Almeida et al. (2012) yields a radial velocity that is not in agreement with theirs and calls into question their identification of this source as a radial velocity variable.
5. GY 30. The Class I source is associated with a fan-shaped near-infrared nebula and a molecular outflow (Kamazaki et al. 2003).
6. ISO-Oph 51. The resolved circumstellar disk displays an asymmetry indicative of planet formation (Cox et al. 2017).
7. GY 91. Millimeter continuum observations exhibit a disk/envelope structure characteristic of an embedded source and have resolved an $r = 80 \text{ au}$ disk with three dark lanes suggestive of planet formation (Sheehan & Eisner 2018).
8. SR 24. SR 24N (SR 24B) and SR 24S (SR 24A) form a wide binary with a separation of $\sim 6''$ within a circumbinary disk (Struve & Rudkjøbing 1949; Mayama et al. 2010; Fernández-López et al. 2017). SR 24N itself is a close binary with a projected separation of 100 mas, an orbital period of 78–216 yr, and a total mass of $1.24 \pm 0.24 M_{\odot}$ (Simon et al. 1995; Correia et al. 2006; Schaefer et al. 2018).
9. SR 24S. Our radial velocity from 2017 of $-0.27 \pm 0.32 \text{ km s}^{-1}$ is significantly different from that derived from optical spectra in 2012 of -8.19 ± 0.33 by Rigliaco et al. (2016), suggesting a binary companion. This velocity variation is much larger than would be expected to arise from interactions with SR 24N. In addition to the photospheric absorption lines, the iSHELL spectrum shows both Brackett gamma and molecular hydrogen ($2.12 \mu\text{m}$) in emission.
10. SR 24N. In addition to the photospheric absorption lines, the iSHELL spectrum shows molecular hydrogen in emission at $2.12 \mu\text{m}$.
11. WL 1. A binary with a $0''.8$ projected separation (Haisch et al. 2002). The primary (WL 1S), which is 0.1 mag brighter at K, was presumably centered in the $0''.58$ NIRSPEC slit. The radial velocity of -25 km s^{-1} is far from the median value for our sample.
12. GY 197. Deep near-infrared images reveal a bipolar outflow cavity centered on the source (Hsieh et al. 2017).
13. WL 17. The radial velocities we derive from spectra obtained in 2001 and 2012 are in good agreement but not consistent with the values reported by Viana Almeida et al. (2012). High spatial resolution ALMA images reveal a transition disk in a disk/envelope system, suggesting that planets can form at an early embedded stage (Sheehan & Eisner 2017). Dynamical clearing by a close companion seems to be ruled out by the lack of variability in the radial velocity.
14. GY 224. The radial velocities from spectra obtained in 2001 and 2008 are consistent.
15. WL 19. The radial velocity of -27 km s^{-1} is far from the median value for our sample. The weak mid-infrared emission and lack of compact dust and gas emission have led to the suggestion that it is not an embedded source but a heavily reddened Class III object behind the molecular cloud (Bontemps et al. 2001; Van Kempen et al. 2009). It is, however, an X-ray source (Imanishi et al. 2001), suggesting that it is a cluster member.
16. GY 235. Our best-fit temperature agrees very well with that derived from moderate-resolution infrared spectra (Manara et al. 2015). In addition to the photospheric absorption lines, the iSHELL spectrum shows both Brackett gamma and molecular hydrogen ($2.12 \mu\text{m}$) in emission.
17. WL 20. Two components of this triple system, WL 20E and WL 20W, were observed. They were easily resolved with a projected separation of $3''.2$ (Ressler & Barsony 2001). Our best fit for WL 20E is warmer than reported by Barsony et al. (2002).
18. WL 4. A periodic variable has been modeled as an equal-brightness triple system (Plavchan et al. 2008) with a heretofore unobserved close binary (WL 4a/4b, 0.47 au) and a known $0''.176$ companion WL 4C at 120 au (Ratzka et al. 2005).

19. WL 3. Our derived value for $v \sin i$ of 41 km s^{-1} is higher than that of Greene & Lada (1997) but consistent with that derived from the same spectrum by Doppmann et al. (2005).
20. WLY 2-43/YLW 15. VLA observations show this to be a $0''.6$ binary also observed in the mid-infrared (Curiel et al. 2003). Our fits suggest a K3 spectral type.
21. WLY 2-44/YLW 16a. Infrared imaging reveals two components of equal brightness at $3.8 \mu\text{m}$ with a projected separation of $0''.3$ (Terebey et al. 2001; Plavchan et al. 2013). A possible third component is suggested from the periodic photometric variability. Radial velocities derived from spectra in 2001 and 2012 show evidence for variability.
22. VSSG 18/WLY 2-35. Radial velocities derived in 2008 and 2012 suggest that it is a radial velocity variable; however, our velocity from 2008 does not agree with Viana Almeida et al. (2012). Luhman & Rieke (1999) assigned a spectral classification of K6.5, which is consistent with our best-fit temperature.
23. VSSG 17/WLY 2-47. This source is a subarcsecond binary with a projected separation of $0''.25$ (Costa et al. 2000). Radial velocities derived from spectra in 2001 and 2012 do not show evidence of variability. Spectral classifications vary from K8 to M2 (Greene & Lada 1997; Luhman & Rieke 1999). Our MCMC results favor the late K classification. Our $v \sin i$ of 41 km s^{-1} agrees well with previous estimates of $43\text{--}47 \text{ km s}^{-1}$ (Greene & Lada 1997; Doppmann et al. 2005).
24. GY 314/WSB 52. Spectral classifications vary from K5 to M3 (Greene & Lada 1997; Luhman & Rieke 1999; Doppmann et al. 2005). Our MCMC results favor the later spectral classification.
25. WLY 2-51. A faint companion ($\Delta K = 3.5 \text{ mag}$) with a projected separation of $1''.6$ has been reported by Ratzka et al. (2005). The iSHELL spectrum suggests weak Brackett gamma emission.
26. WLY 2-54. The iSHELL spectrum is devoid of photospheric absorption lines but does show Brackett gamma and molecular hydrogen ($2.12 \mu\text{m}$) in emission. The spectrum also displays narrow interstellar absorption lines from low R and P branch lines from the CO $v = 0\text{--}2$ transitions.

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