Identification of Main Sequence Stars with Mid-Infrared Excesses Using GLIMPSE: β-Pictoris Analogs?

B. Uzpen, 1 H.A. Kobulnicky, 1 K. A. G. Olsen, 2 D. P. Clemens, 3 T.L. Laurance, 1 M. R. Meade, 4 B. L. Babler, 4 R. Indebetouw, 4 B. A. Whitney, 5 C. Watson, 4 M. G. Wolfire, 6 M. J. Wolff, 5 R. A. Benjamin, 7 T. M. Bania, 3 M. Cohen, 8 K. E. Devine, 4 J. M. Dickey, 9 F. Heitsch, 10 J. M. Jackson, 3 A. P. Marston, 11 J. S. Mathis, 4 E. P. Mercer, 3 J. R. Stauffer, 12 S. R. Stolovy, 12 D.E. Backman, 13 and E. Churchwell 4

ABSTRACT

Spitzer IRAC 3.6-8 μm photometry obtained as part of the GLIMPSE survey has revealed mid-infrared excesses for 33 field stars with known spectral types in a 1.2 sq. degree field centered on the southern Galactic H II region RCW49. These stars comprise a subset of 184 stars with known spectral classification, most of which were pre-selected to have unusually red IR colors. We propose that the mid-IR excesses are caused by circumstellar dust disks that are either

1University of Wyoming, Dept. of Physics & Astronomy, Dept. 3905, Laramie, WY 82071
2Cerro Telolo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena Chile
3Boston University, Institute for Astrophysical Research, 725 Commonwealth Ave., Boston, MA 02215
4Space Science Institute, 4750 Walnut St. Suite 205, Boulder, CO 80301
5University of Wisconsin-Madison, Dept. of Astronomy, 475 N. Charter St., Madison, WI 53706
6University of Maryland, Dept. of Astronomy, College Park, MD 20742-2421
7University of Wisconsin-Whitewater, Physics Dept., 800 W. Main St., Whitewater, WI 53190
8University of California-Berkeley, Radio Astronomy Lab, 601 Campbell Hall, Berkeley, CA 94720
9University of Minnesota, Dept. of Astronomy, 116 Church St., SE, Minneapolis, MN 55455
10Institute for Astronomy & Astrophysics, University of Munich, Scheinerstrasse 1, 81679 Munich
11ESTEC/SCI-SA, Postbus 299, 2200 AG Noordwijk, The Netherlands
12Caltech, Spitzer Science Center, MS 314-6, Pasadena, CA 91125
13SOFIA, MS 211-3, NASA-Ames Research Center, Moffett Field, CA 94035-1000
very late remnants of stellar formation or debris disks generated by planet formation. Of these 33 stars, 29 appear to be main-sequence stars based on optical spectral classifications. Five of the 29 main-sequence stars are O or B stars with excesses that can be plausibly explained by thermal bremsstrahlung emission, and four are post main-sequence stars. The lone O star is an O4V((f)) at a spectrophotometric distance of $3233^{+540}_{-535}$ pc and may be the earliest member of the Westerlund 2 cluster. Of the remaining 24 main-sequence stars, 18 have SEDs that are consistent with hot dusty debris disks, a possible signature of planet formation. Modeling the excesses as blackbodies demonstrates that the black-body components have fractional bolometric disk-to-star luminosity ratios, $L_{IR}/L_*$, ranging from $10^{-3}$ to $10^{-2}$ with temperatures ranging from 220 to 820 K. The inferred temperatures are more consistent with asteroid belts rather than the cooler temperatures expected for Kuiper belts. Mid-IR excesses are found in all spectral types from late B to early K.

*Subject headings:* (Stars:) circumstellar matter; planetary systems:formation; Westerlund 2

1. Introduction

IRAS observations of Vega detected an infrared excess above the photospheric level, suggesting the presence of circumstellar material (Aumann et al. 1984). Follow-up observations found infrared excesses around other main-sequence stars, including β Pictoris. Coronographic imaging identified a resolved dusty disk around β Pictoris as the cause of the infrared excess (Smith & Terrile 1984). β Pictoris’s disk is a prototype for a young, but nearly complete planetary system. Identification of this disk was the first observational evidence of planetary systems outside our own. Many nearby stars have been investigated using IRAS and ISO to search for far-IR photospheric excesses, and a large number have been found (Lagrange et al. 2000; Backman et al. 1993; Chen et al. 2005 and references therein). Due to the large beam size of IRAS, far-IR observations of nearby stars such as β Pictoris, ε Eradani, Fomalhaut, and others have resulted in follow-up higher resolution ground based mid-IR observations that resolved their disks and probed their compositions (Lagrange et al. 2000; Backman et al. 1993; Chen et al. 2005 and references therein). Due to the large beam size of IRAS, far-IR observations of nearby stars such as β Pictoris, ε Eradani, Fomalhaut, and others have resulted in follow-up higher resolution ground based mid-IR observations that resolved their disks and probed their compositions (Lagrange et al. 2000; Backman et al. 1993; Chen et al. 2005 and references therein).

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1 Visiting astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation.
Stars with far-IR excesses such as $\epsilon$ Eradani may even harbor planets (Hatzes et al. 2000).

Only a few main-sequence stars with mid-IR but no near-IR excesses have been detected. Aumann & Probst (1991) investigated nearby main-sequence stars using 12 $\mu$m measurements from IRAS, but out of the 548 stars investigated, only 13 stars had colors unusual enough to warrant further investigation. Follow up ground-based observations were conducted on 7 stars at 10 $\mu$m to determine if the excess originated from the star. Only $\beta$ Pictoris and $\zeta$ Leporis exhibited mid-IR excesses (Aumann & Probst 1991). Chen & Jura (2001) measured a temperature of 370 K for the mid-IR excess in $\zeta$ Leporis and suggest that it is due to a massive asteroid belt. The excess in $\zeta$ Leporis originates at small radii, less than 6 AU, and not at large radii, $\geq$40 AU, unlike other stars such as $\beta$ Pictoris which have large disks extending hundreds of AU (Chen & Jura 2001). Stars with higher disk temperatures have dust which is closer to the star, and the excess may be more analogous to the warm temperatures of asteroid belts than to the $\sim$100K dust of Kuiper belts.

Evidence for planets around nearby stars is now overwhelming with over 120 planets in 100+ planetary systems, most found using high resolution stellar spectroscopy capable of detecting Doppler shifts in the parent star. However, the process or processes by which these planets form is still unknown. Planetesimals may originate in circumstellar disks, formed as a by-product of star formation. The evolutionary sequence of both inner and outer circumstellar disks from pre-main sequence to main-sequence is not well understood (Meyer & Beckwith 2000). Lack of observational evidence of an evolutionary disk sequence is a major hindrance in the understanding of planetary formation. The reason for this lack of evidence is that only the nearest stars have been probed for circumstellar disks, and a relatively small number of stars with disks have been identified. It is estimated that at least 15% of nearby A-K main-sequence stars have dusty debris disks that were detectable to IRAS and ISO sensitivities in the far-infrared (Lagrange et al. 2000; Backman & Paresce 1993).

The Spitzer Legacy program includes two surveys investigating the formation of stars and the processes leading to the formation of solar systems: the “Cores to Disks” (C2D; Evans et al. 2003) and “Formation and Evolution of Planetary Systems” (FEPS; Meyers et al. 2001) projects. Data from these programs will cover a large portion of the spectral energy distribution (SED) of stars as well as provide insight into the structure and evolution of circumstellar disks. The focus of the C2D project is on stellar cores and very young stars with ages up to $\sim$10 Myr. The FEPS project focuses on older solar analogues, 3 Myr to 3

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2Extrasolar Planet Encyclopedia http://cfa-www.harvard.edu/planets
Gyr, to determine disk composition and characterize their evolutionary stages. The FEPS and C2D projects are, however, narrowly focused in spatial coverage, with C2D covering \(\sim 20 \text{ sq. degree}\) and FEPS focusing on \(\sim 350\) individual stars out to \(\sim 200 \text{ pc}\).

In this present study, we have utilized a subset of the Galactic Legacy Infrared MidPlane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003) database to try to identify main-sequence stars with mid-infrared excesses. Given the sensitivity of the Spitzer Space Telescope Spitzer, we expect to be able to detect unreddened A stars to \(\sim 4 \text{ kpc}\), F stars to \(\sim 2 \text{ kpc}\), G stars to \(\sim 1.3 \text{ kpc}\), and K stars to \(\sim 1 \text{ kpc}\). Given these distances we will survey a much larger volume of space for stars exhibiting mid-IR excesses than any previous study.

Optical spectra were obtained to determine if near and mid-infrared colors could indicate a spectral sequence. In this paper, we present results of a survey of the GLIMPSE Observation Strategy Validation (OSV) region in the vicinity of the southern Galactic star-forming region RCW 49, where the Westerlund 2 open cluster is centered (Churchwell et al. 2004). We obtained optical spectroscopy for a sample of stars with red or unusual near and mid-infrared colors. We combine optical photometry and spectroscopy with near and mid-infrared photometry to model the SEDs of the stars. Once a star is shown to exhibit a mid-IR excess, we model the excess as a single blackbody to gain some insight into its basic properties. In Section 2, we discuss the photometry obtained with GLIMPSE and the method of classification of spectral types. In Section 3, we discuss how stars with mid-IR excesses were identified, and in Section 4 we compare the stars with mid-IR excesses to the prototype debris disk system, \(\beta\) Pictoris. In Section 5 we discuss the lone O4V((f)) star which exhibits a mid-IR excess and its implications for the age and distance of Westerlund 2. This is a preliminary investigation to determine if warm debris disks can detected with the GLIMPSE survey in the mid-IR.

2. Data

2.1. GLIMPSE Photometry

The GLIMPSE project is one of six Spitzer Legacy Programs. GLIMPSE mapped the Galactic Plane in four infrared array camera (IRAC; Fazio et al. 2004) band passes, \([3.6],\) \([4.5],\) \([5.8],\) and \([8.0] \mu \text{m}\) from \(|l| = 10^\circ - 65^\circ\) and \(|b| < 1^\circ\) degrees (Benjamin et al. 2003). This survey has generated a point source catalog of \(3 \times 10^7\) objects. The GLIMPSE program is the largest, most sensitive, mid-infrared survey to date. The GLIMPSE program mapped RCW49 as part of the OSV (Churchwell et al. 2004). This region was mapped 10 times with 1.2 second exposures by IRAC and is therefore the deepest region surveyed by the
GLIMPSE program. A total of 38,734 mid-infrared catalog sources were found in the OSV. To be included in the Point Source Catalog, a source must have a signal-to-noise ratio of greater than 5:1 with at least two detections in one band and at least one detection in an adjacent band with fluxes greater than 0.6 mJy, 0.6 mJy, 2 mJy, and 10 mJy (in Bands 1 through 4, respectively). The other two bands need only have a signal-to-noise ratio of greater than 3:1. See the GLIMPSE data document\(^3\) or Mercer et al. (2004), Churchwell et al. (2004), Whitney et al. (2004), or Indebetouw et al. (2005) for further descriptions.

2.2. Spectra

We obtained optical spectroscopy of 220 stars in the GLIMPSE OSV field surrounding RCW49 using the Hydra instrument on the CTIO 4m on the night of 2004 March 1 using three fiber configurations. The instrument configuration used the large 2 arcsecond fibers and the KGFL1 grating, which provides a dispersion of 0.6 Å/pixel, a spectral resolution of 4.2 Å, and wavelength coverage of \(\sim2400\) Å from \(\sim3600 – 6000\) Å. This wavelength regime covers the majority of the Hydrogen Balmer series, Ca H and K, as well as many metal lines which are necessary for luminosity and temperature classification. Total exposure times were 20 minutes for the first fiber configuration and 60 minutes for the second and third fiber configurations. Sky conditions were photometric.

We selected target stars based on preliminary GLIMPSE photometry in all 4 IRAC bandpasses along with 2MASS\(^4\), and Guide Star Catalog 2.2 (GSC\(^5\)) photometry. The stars were selected using optical brightness and infrared colors. The stars in the first fiber configuration consisted of High-Precision Parallax-Collecting Satellite (Hipparcos) and Tycho

\(^3\)GLIMPSE Team Webpage http://ssc.spitzer.caltech.edu/legacy

\(^4\)This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

\(^5\)The Guide Star Catalogue-II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, for the National Aeronautics and Space Administration under contract NAS5-26555. The participation of the Osservatorio Astronomico di Torino is supported by the Italian Council for Research in Astronomy. Additional support is provided by European Southern Observatory, Space Telescope European Coordinating Facility, the International GEMINI project and the European Space Agency Astrophysics Division. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France.
Catalog stars and bright GSC stars with \( V \leq 13 \). Bright stars with 2MASS/IRAC colors indicative of possible IR excesses were also placed in the first two fiber fields. We selected stars with colors indicating an IR-excess or extreme reddening as those which satisfied one or more of the following criteria: flux ratios \( \log \frac{F_{8.0}}{F_{3.6}} \geq -0.5 \) (criterion 1), \( \log \frac{F_{K}}{F_{J}} \geq 0.15 \) (criterion 2), or \( \log \frac{F_{5.8}}{F_{3.6}} \geq -0.25 \) (criterion 3). We chose these criteria to sample a representative distribution of objects with unusual infrared colors. Criterion 1 sources comprise the reddest \( \sim 15 \% \) of sources with visual counterparts, criterion 2 sources comprise \( \sim 2 \% \), and criterion 3 comprise \( \sim 13 \% \). Color-color plots of the data set used in selecting stars are shown in Figure 1. Stars that met criterion 1, 2, and 3 are plotted as green, red, and blue pluses respectively. Figure 1 gives a representative view of the color-color space occupied by the stars meeting one or more of the three criteria.

The second fiber field consisted of stars with GSC photometry and IR colors satisfying one or more of the three color criteria. The third fiber field consisted of stars meeting one or more of the color criteria, but some stars did not have GSC \( V \)-band counterparts, allowing for the inclusion of extremely red stars.

A total of 164 new stellar classifications resulted from these observations. The stars were classified by eye using comparison spectra (Yamashita et al. 1976) to within two comparison temperature classes of the atlas. There were 56 stars too faint or featureless for classification. Protostars may comprise a significant fraction of these unclassified objects because they have high extinctions and are optically faint. There are \( \sim 50 \) stars in the OSV that had previous spectral classifications in the literature, but most of them were saturated in GLIMPSE so their mid-IR colors are, therefore, unreliable and are not included in this investigation. We were able to use 20 stars that had suitable GLIMPSE colors and were previously classified in the literature.

3. Analysis

The positions of 38,734 GLIMPSE Point Source Catalog objects in the OSV were matched against the positions of 2MASS Point Source Catalog objects using the GLIMPSE data reduction pipeline. We then matched the Guide Stars with the GLIMPSE objects to produce V, J, H, K, [3.6], [4.5], [5.8], [8.0] photometry for the 184 spectrally classified stars, although some objects lack photometry at one or more of the eight bandpasses. The GSC V-band photometry was extracted from photometric plates, and most stars have V-band uncertainties of \( \sim 0.4 \) magnitudes, (see the GSC documentation for more information).

The eight photometric data points were fit with Kurucz ATLAS9 models using tem-
temperatures and effective gravities corresponding to the nearest spectral type (Kurucz 1993). Since all of the stars lie within the solar circle, we adopt the solar metallicity models. The Kurucz model surface fluxes were scaled by a factor, $X$, so that the model K-band fluxes matched the observed K-band 2MASS photometry. This scale factor represents $X = R^2/D^2$, the ratio of the stellar radius squared over the distance to the star squared. Adopting stellar radii appropriate for the observed spectral types (De Jager, C. & Nieuwenhuijzen, H. (1987), Schmidt-Kaler, Th. (1982), Johnson, H.L. (1966)), we calculated a spectrophotometric distance to each star. These distances and their uncertainties estimated by taking into account the K-band photometric errors added in quadrature with an additional 15% uncertainty in the stellar radii are listed in the tables. The K-band measurements were used as the basis for the distance computation because the effects of extinction are nearly negligible at 2.2 $\mu$m for most of our stars. Our derived $A_V$ are all $< 1.5$ mag implying $A_K < 0.15$ mag. The model atmospheres were reddened with variable amounts of extinction using the Li & Draine (2001) extinction curve, except in the mid-infrared ($\lambda > 3 \, \mu m$) where the GLIMPSE extinction results were used (Indebetouw 2005). Distance and extinction were fit iteratively as free parameters covering a grid of all reasonable values. The best fit parameters for each star are determined by the minimum of the $\chi^2$ statistic. Modeling the star with the next earlier or later spectral type model available in the Kurucz library (i.e., an A3 with an A0 or an A5) produced very similar reduced $\chi^2$ values. This allows small errors in classification to yield similar results. This also provides a check on classification. If a star is grossly misclassified the fit is poor and the classification is double checked.

We performed a trial fitting procedure in which the effective temperatures and gravities of the stellar models were allowed to vary as free parameters (i.e., the program searched through the entire library of Kurucz models to find a best fit). In nearly all cases, this method produced fits with lower $\chi^2$, but this approach frequently converged upon temperature and gravity combinations which were grossly inconsistent with the observed spectral types. We found that there was often a degeneracy between the amount of extinction and the effective temperature, such that models with high temperatures and low extinctions yielded similar fits as models with low temperatures and high extinctions. We, therefore, chose to fix the effective temperatures and gravities of the models at value appropriate to the classified spectral type.

Our data set consisted of 184 main-sequence, giant, and supergiant stars with spectral types in the OSV region. This sample included 20 stars with known spectral types from the literature which had reliable GLIMPSE photometry as well as the 164 sources for which we obtained new classifications. We calculated ($K - 8$) color excesses, $E(K - 8)$, by taking the differences between the Kurucz photospheric model and the photometric ($K - 8$). We chose the ($K - 8$) color because main-sequence stars should exhibit minimal color differences for
these wavelengths. This method is similar to the method used by Aumann & Probst (1991), in which $K - 12$ from IRAS was used to identify warm disk candidates.

Figure 2 shows the $E(K - 8)$ distribution of stars with $(K - 8)$ colors. The distribution shows a peak with a mean near $E(K - 8)=0.08$ and a long tail toward larger excesses. The majority of stars, 110, have $E(K - 8)$ between -0.2 and 0.35 with a mean of 0.08 and a dispersion of 0.09. There were 33 stars with excesses larger than three times the dispersion of the main group, i.e., with an $E(K - 8) \geq 0.35$. Of these 33 stars with possible mid-IR excesses, three did not have measurements at $[5.8]$, and three of the stars had photometric uncertainties placing them within one standard deviation from an $E(K - 8)$ of 0.35. In order to place a higher reliability on our detections we required that the stars have all four IRAC measurements, and an $E(K - 8) \geq 0.35 + 1 \sigma$. Table 1 gives the colors and uncertainties for the 18 main sequence stars satisfying the above criteria, along with their spectral types and color uncertainties. Hereafter, we refer to this group of stars as the ”G18” sample. Table 2 contains the stars that had an excess greater than 0.35 but did not meet all of our criteria for inclusion in Table 1. Table 2 include stars which did not have all 4 IRAC measurements, or stars of early spectral type where the excess could be explained by thermal bremsstrahlung emission (See 3.1).

Figure 3 shows color-color plots of the stars with mid-IR excesses. Panel A shows that the stars with a $(K - 8)$ excess exhibit typical colors for the J,H,K near-infrared, but in Panel D they show a significant deviation from the main-sequence which can not be explained by reddening. Stars which could not be classified because of insufficient signal to noise in the optical spectra are shown only in panel B because almost all of these stars were in Field 3 and did not have a V band measurement. Triangles denote stars with a mid-IR excess that did not have V-band measurements. Nearly all of the unidentified stars have $F_{K}/F_{J}$ much redder than the stars exhibiting mid-infrared excesses. These stars are likely to be highly extinguished and could be protostars.

3.1. The Mid-IR Excesses

We analyzed the SED’s of the 23 stars meeting the above ”excess” criteria to determine whether phenomena other than disks could explain their mid-IR excesses. An unresolved close stellar companion cannot produce the observed IR-excess. For most of the stars in Table 1, their mid-IR excesses are only significant at $[8.0]$. A companion dwarf star of G, K, or M spectral class would raise the photometric flux at wavelengths $\leq 1 \mu m$ to a much greater degree than in the mid-IR, and such additional stellar components are inconsistent with the observed SEDs. Even with stellar additional companions, the $[8.0]$ measurements are
still above expected photospheric levels. If any of our targets are multiple star systems, the primary star dominates the SED and a diskless companion would not contribute significantly to the SED.

We investigated the GLIMPSE residual images after PSF fitting photometry and subtraction to rule out the possibility of systematic photometric errors. There were no significant residuals in the pixels at or surrounding each star’s location. If larger photometric uncertainties in high background or highly structured background regions produced spurious signatures of \((K - 8)\) excesses, we would expect to see as many stars with negative \(E(K - 8)\) as positive \(E(K - 8)\). The distribution in Figure 2, however, shows only significant positive \(E(K - 8)\) values. If the excess is due to only PAH features, we would expect to see an enhancement at \([3.6], [5.8], [8.0]\) with respect to \([4.5]\) since \([4.5]\) is devoid of PAH features. None of our excess sources exhibit this enhancement.

Thermal bremsstrahlung emission could possibly explain the \(E(K - 8)\) values seen in the three early B stars and one O star listed in Table 2. These stars generally have all 4 IRAC measurements in excess of the photosphere model values. An optically thin, thermal bremsstrahlung component was included in the modeling of their SEDs. The luminosity of the bremsstrahlung component was allowed to vary as a free parameter along with extinction and distance. These models with bremsstrahlung components fit the SEDs much better than the models with a single blackbody component. A blackbody component model with a single temperature is insufficient to fit all four measurements in excess of the photosphere. Since these are ionizing stars and they fit a thermal bremsstrahlung model, we feel that this is the most likely explanation for the mid-IR excess of these four stars.

In conclusion, we note that the characteristic temperature of the blackbody component which creates a significant excess at 8 \(\mu\)m, but not at shorter wavelengths, is \(\sim400\) K because a 400 K blackbody peaks at 7.4 \(\mu\)m. Even the coolest known brown dwarfs (Burgasser et al. 2000; Burrows et al. 2001) have temperatures of \(\sim700 – 750\) K, and Jupiter-like planets would be insufficiently luminous to create the observed infrared excesses. We conclude that the source of the mid-IR excess for the stars in Table 1 is probably warm \(\sim400\) K dust.

4. Discussion

An SED of \(\beta\) Pictoris, the prototype debris disk system, is shown in Figure 4 for comparison to the excess candidates. Figure 4 also shows the appropriate Kurucz model. The SED is comprised of L (3.45 \(\mu\)m), M (4.50 \(\mu\)m), N (10.1 \(\mu\)m), and Q (20 \(\mu\)m) measurements from Backman et al. (1992). The Q band measurement was included so that the number
of data points and the wavelength range was similar for both β Pictoris’s model and the G18 stars (8 measurements and 4 free parameters in the model). The GSC and 2MASS measurements were used to model β Pictoris in a manner equivalent to that for the G18 stars. Comparing the 2MASS photometry to near-IR measurements in the literature for β Pictoris shows that the near-IR photometry is consistent, but 2MASS data have much larger uncertainties, approximately 20%. Our spectrophotometric distance of 22.5 ± 3.0 pc for β Pictoris is consistent with the Hipparcos distance of 19.28 ± 0.19 pc.

In order to estimate the sizes and temperatures of any dust disks for the G18 stars, we modeled the excess in each star as a single black body with temperature and fractional bolometric disk-to-star luminosity ratio, $L_{IR}/L^*$, as free parameters. This assumption, although simplistic, yields a rough approximation to the temperatures and $L_{IR}/L^*$ of the dust disks, given the limited number of photometric points available. We searched a grid of blackbody temperatures and fractional disk luminosities to find best fits to the observed data. The temperature grid ranged from 100 K to 1100 K in steps of 1 K. This model was used to estimate the most probable parameters for the dust disks. For our model of β Pictoris, we found a single temperature for the excess to be $223^{+4}_{-4}$ K with the disk emitting $0.0019^{+0.0002}_{-0.0002}$ the luminosity of the star. In comparison, Gillett (1986) fit a single temperature blackbody to both mid-IR and far-IR data, from which they infer a temperature of 103 K and a fractional luminosity of 0.003 for β Pictoris. By fitting the mid-IR data alone we may be overestimating the disk temperature or just measuring the hotter inner portion of a larger disk. Chen & Jura (2001) found the color temperature of ζ Leporis to be 370 K, but they note that if they only fit the data at wavelengths greater than 10 μm the disk temperature is better fit by a 230 K blackbody. Backman et al. (1992) use a two disk component for β Pictoris and find the inner disk temperatures to range from 200-400 K depending on the model used. Therefore the temperature we estimate for the debris disk is consistent with the range of disk temperatures given in Backman et al. (1992) from a variety of more sophisticated models.

We investigated the likelihood of other disk temperature/fractional luminosity combinations using a Monte Carlo simulation to determine the uncertainties on our derived disk and star parameters. The Monte Carlo code adds Gaussian noise to each of the photometric data points (based on their 1 σ photometric errors) and then re-computes the most probable distance, visual extinction, blackbody temperature, and fractional blackbody luminosity. Figure 5 shows a plot of the Monte Carlo simulation results for β Pic. The photometry and model constrain the temperature and fractional luminosity to a small region of the parameter space. Even a few near and mid-IR photometric measurements effectively constrain the temperatures and fractional disk luminosities. Figure 6 shows the distribution functions of distance (before adding the 15% stellar radii uncertainty), visual extinction, blackbody temperature, and fractional luminosity for β Pictoris. Both the blackbody temperature and
fractional luminosity are well constrained in this simulation. Spectrophotometric uncertainties are primarily due to the assumption for the stellar radii uncertainties but are still well constrained. With only the visual measurement in the optical, there is some variation in extinction but for most stars the extinction is low. Distributions for all the derived parameters are nearly Gaussian.

We then conducted the same analysis on our candidate stars. In a small fraction of the Monte Carlo simulations, $\leq 5\%$ for most stars, the best fit parameters require a fractional disk-to-star luminosity ratio greater than unity. We discard these Monte Carlo iterations as unphysical. In order for the luminosity of the disk to exceed the luminosity of the star, the star would have to be embedded in a region which required re-emission of absorbed stellar light, or generation of energy by the disk. This would occur in early protostars, Class 0 or I, but not in more evolved pre main-sequence stars. Three stars, G284.1744-00.5141, G284.0110-00.1208, and G283.9773-00.3948, had greater than 10% of their Monte Carlo simulations yield unphysical fractional disk luminosities. These 3 stars have an excess only at $8\,\mu m$ which provides weaker constraints on the fractional disk luminosity and temperature. Table 3 lists derived parameters and their uncertainties based on the median values of the Monte Carlo simulation.

Figure 7 shows the SED for one of our G18 stars, the A3V star G284.3535-00.2021. The thick solid line is the Kurucz model, the dot-dash line is the SED of the disk component, and the thin line is the combination of the Kurucz model with extinction plus the SED of the disk component.

Figure 8 shows the results for 2000 Monte Carlo iterations, demonstrating that higher temperatures paired with lower fractional luminosities occur more readily than lower temperatures with higher fractional luminosities. This plot of fractional disk luminosity versus temperature demonstrates that there is an anti-correlation between fractional disk luminosity and temperature. When blackbody temperature is high, the fractional disk luminosity is low, and when temperature is low fractional disk luminosity is high. The median temperature from the simulations is 385 K (i.e., $\sim$160 K warmer than $\beta$ Pictoris), consistent with the observation that the excess appears at shorter wavelengths in G284.3535-00.2021. The models constrain the temperature to $385^{+70}_{-56}$ K and the fractional disk luminosity to $0.0043^{+0.0014}_{-0.0010}$.

Figure 9 shows the distribution of distance (before adding the 15% stellar radii uncertainty), visual extinction, temperature, and fractional luminosity for G284.3535-00.2021 determined from Monte Carlo simulations. This distribution is much broader than that for $\beta$ Pictoris due to our limited ability to constrain maximum possible temperatures with data shortward of $8\,\mu m$. Longer wavelength data, in both the mid and far-IR, would allow us to
better constrain the temperature and fractional luminosity.

Table 3 lists the derived parameters and their uncertainties for all 18 main-sequence, non O and B stars with an excess (in the G18 sample). The temperatures for the excesses range from 220-820 K with fractional luminosities ranging from $10^{-3}$ to $10^{-2}$. Figure 10 shows both temperature and fractional luminosity ratio histograms for the remaining 17 stars in the G18 sample. For star 11 a large portion of the fractional luminosity ratio was below $10^{-3}$ and is therefore off the scale. This is because there is a significant excess at only [8.0]. G284.0110-00.1208 and G284.0719-00.1637 have broad distributions, again due to the weaker constraints on the excess. Figure 10 demonstrates the large variation in temperature and fractional luminosity distribution between stars. Figure 11 shows the distribution of both temperature and fractional luminosity for all G18 stars. The median temperature for the sample is $\sim 500$ K. There does not appear to be a correlation between either temperature or fractional disk luminosity with spectral type but the sample is small. Future work may reveal a correlation of either disk temperature or fractional luminosity with spectral type.

4.1. Protostellar Disk or Debris Disk?

Lagrange et al. (2000) suggest a definition of debris disks using four criteria. These criteria include the bolometric fractional disk-to-star luminosity $\leq 10^{-3}$, the mass of the gas and dust to be below $10^{-2} M_\odot$, the dust mass significantly greater than the gas mass, and the grain destruction time much less than the stellar age. Our limited data only allow comparisons based on the fractional bolometric luminosity.

Since $\frac{L_{\text{IR}}}{L_\ast} \leq 0.1$ for all of the G18 stars, these stars are debris disks or may be in a transitionary phase from protostellar to debris disk. Although these stars have blue spectra which lack emission lines, except G284.3417-00.2049 which exhibits H\(\beta\) emission, and appear to be main-sequence, we can not rule out H\(\alpha\) emission. Weak H\(\alpha\) emission could be present, without H\(\beta\) emission, which could imply that the star is pre main-sequence. We can not rule out the possibility that the stars may have primordial disks, but the disks are most likely to be debris disks. Protostars typically have $\frac{L_{\text{IR}}}{L_\ast} \geq 0.1$ and debris disks typically have $\frac{L_{\text{IR}}}{L_\ast} \sim 10^{-3}$ (Lagrange et al. 2000; Backman & Paresce 1993). Since G284.1744-00.5141, G284.0110-00.1208, and G283.9773-00.3948 had a large number of their Monte Carlo iterations discarded because they were unphysical, their fractional disk luminosities may be greater than tabulated in Table 3. These stars may be protostellar in nature since the models allow higher fractional luminosities, but their derived luminosities, omitting the unphysical simulations, are still consistent with debris disks. Mid-IR spectral analysis of the stars in Table 3 would reveal whether the 10 \(\mu\)m silicate feature is present and would be a useful tool
in the characterization of mid-IR excesses around main-sequence stars. The absorption (embedded protostar), emission (pre main-sequence), or lack of the 10 μm silicate feature (debris disk) is loosely related to the evolutionary progression of a circumstellar disk (Kessler-Silacci et al. 2005). However, the debris disks studied by Kessler-Silacci et al. (2005) contained debris disks that only exhibited far-IR excesses. β Pictoris, a mid-IR debris disk system, does have a 10 μm silicate emission feature. A useful comparison would be to determine whether this sample of mid-IR debris disk systems also exhibits a 10 μm silicate emission feature.

5. G284.2642-00.3156

One especially interesting star that exhibited a mid-IR excess is G284.2642-00.3156. The optical spectrum of this early type star is shown in Figure 12. Using the OB star spectral atlas of Walborn & Fitzpatrick (1990) we classify this star as O4V((f)). The classification is based on the relative strength of He I, He II, and the hydrogen Balmer series. Figure 12 shows that for this star weak N III 4634-40-42 Å appears in emission and a strong He II 4686 Å appears in absorption, which implies that the star is earlier than O5. He I is present in absorption but is very weak, which implies that the star is later than O3 since an O3 lacks He I absorption. We did not see any N IV 4058 Å emission or any significant N V 4604 Å or 4620 Å absorption, and He II 4686 Å is in absorption. These imply that the star is not a supergiant or giant.

Figure 13 and Figure 14 show GLIMPSE [3.6] and [8.0] images in the region surrounding G284.2642-00.3156, including Westerlund 2. G284.2642-00.3156 is marked by the white box. The [3.6] image shows that G284.2642-00.3156 is surrounded by a grouping of faint stars which are partially blended with the O4 star at the 1.22 arcsecond angular resolution of the IRAC 3.6 μm array. We determine a spectrophotometric distance to this star of 3233^{+540}_{-535} pc with a visual extinction of 5.63^{+0.01}_{-0.30}. The [8.0] image shows a nearly circular ring with radius of ∼38'' surrounding the O star. At a distance of 3.5 kpc, the ring around the star would be 0.65 pc in diameter. This could be a wind blown shell illuminated by the star. There is also an irregular linear feature extending 29'' from the star in the northwest direction. This feature may be a nearby cloud illuminated by the star, or may trace the relative motion of the star through the inter-stellar medium surrounding Westerlund 2.

Using the images of Moffat et al. (1991) we identify G284.2642-00.3156 as their star #18, which they find to be the most luminous star in the cluster. They type this star as an O7V, but they note that its absolute luminosity is brighter than that of an O7V. Moffat et al. conclude that since the star appears isolated, it must, by color and luminosity arguments, be a supergiant if it lies at the distance of the cluster. Our new classification results in an
earlier spectral type with an extinction which is still consistent with cluster membership, but a distance that is not consistent with the 7.9 kpc by Moffat et al. (1991). We note that the distance we find for the O4V((f)) star is inconsistent with the Carraro & Munari (2004) cluster distance of 6.3 kpc but still consistent with the wide variation of distances found for this cluster (Churchwell et al. 2004). If this star is a cluster member it would be the earliest known member. Moffat et al. (1991) assumed a cluster age of 2-3 Myr based on the presence of the O7 stars. The proximity of WR20b to the cluster may imply an older age of 3-5 Myr if it is also a cluster member (Shara et al. 1991). The lifetime for an O4 is on the order of 3 Myr (for a 60 $M_{\odot}$ star with Z=0.02; Meynet et al. 1994). G284.2642-00.3156 lies 1 arcminute from the cluster center, which corresponds to a minimum projected separation of 1 pc if the star is at a distance of 3.5 kpc. In order to travel 1 pc in 3 Myr or less, a modest space velocity of $\geq 0.3$ km s$^{-1}$ is required. Thus the reddening, and projected separation of the O4 star are consistent with cluster membership and origin. This implies that Westerlund 2 may be younger and closer than previously thought. However, G284.2642-00.3156 may have been formed subsequent to the formation of Westerlund 2 as a result of triggered star formation in surrounding molecular clouds (Deharveng et al. 2005, Oey et al. 2005). Further studies will determine if this star is a cluster member or a result of triggered star formation as well as the distance to this cluster. High resolution spectra of both the O4 star and Westerlund 2 would allow a measurement if their relative radial velocities and would help establish whether this star is a cluster member.

6. Conclusion

We found 33 stars which exhibited a mid-IR excess above photospheric levels in the field surrounding RCW49. We combined our new spectral classifications with known literature classifications and optical, near, and mid-infrared photometry to model the spectral energy distributions of 184 stars. Stars with mid-IR excesses span all spectral classes from B to early K. We modeled the excess for each star as a single component blackbody and found that for the G18 stars, the excess is consistent with a debris disk or some transitionary phase between primordial circumstellar disk and debris disk. For these 18 stars the additional black body component was found to have fractional bolometric disk-to-star luminosity ratios, $L_{IR}/L_{*}$, ranging from $(10^{-3}$ to 10$^{-2}$) with temperatures ranging from 220 to 820 K. These temperatures and fractional disk-to-star luminosities are consistent with warm inner dust of debris disks which could be analogous to asteroid belt type objects.

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Table 1. Photometric Parameters for Stars with Mid-IR Excesses

| ID         | 2MASS ID     | K  | σK | V-K | σV-K | J-K | σJ-K | H-K | σH-K | K-[3.6] | σK-[3.6] | K-[4.5] | σK-[4.5] | K-[5.8] | σK-[5.8] | K-[8.0] | σK-[8.0] | Spec. |
|------------|--------------|----|----|-----|------|----|------|----|------|--------|---------|--------|---------|--------|---------|--------|---------|-------|
| 1          | G284.3535-00.2021 | 10250358-5741409 | 11.89 | 0.03 | -0.05 | 0.17 | 0.07 | 0.04 | 0.10 | 0.04 | 0.14 | 0.04 | 0.15 | 0.05 | 0.24 | 0.07 | 0.97 | 0.14 | A3V |
| 2          | G284.1744-00.5141 | 10224039-5751461 | 12.47 | 0.03 | -0.09 | 0.43 | 0.06 | 0.04 | 0.05 | 0.04 | 0.02 | 0.04 | 0.01 | 0.05 | 0.13 | 0.15 | 0.89 | 0.12 | A2V |
| 3          | G283.8842-00.3361 | 10213378-5733229 | 12.66 | 0.03 | 1.98 | 0.44 | 0.55 | 0.04 | 0.11 | 0.04 | 0.14 | 0.04 | 0.08 | 0.05 | 0.45 | 0.11 | 0.45 | 0.08 | K0V |
| 4          | G284.1241-00.2429 | 10232673-5736249 | 10.92 | 0.02 | 0.86 | 0.16 | 0.11 | 0.03 | 0.03 | 0.03 | 0.14 | 0.03 | 0.14 | 0.04 | 0.22 | 0.05 | 0.53 | 0.06 | A7V |
| 5          | G284.0185-00.1803 | 10230188-5729511 | 12.66 | 0.03 | 1.98 | 0.44 | 0.55 | 0.04 | 0.11 | 0.04 | 0.14 | 0.04 | 0.08 | 0.05 | 0.45 | 0.11 | 0.45 | 0.08 | K0V |
| 6          | G284.0547-00.5695 | 10214145-5750415 | 12.73 | 0.04 | 0.99 | 0.43 | 0.21 | 0.05 | 0.07 | 0.05 | 0.10 | 0.05 | 0.11 | 0.06 | 0.40 | 0.09 | 1.27 | 0.23 | B8V |
| 7          | G284.0719-00.1637 | 10232601-5730435 | 12.60 | 0.03 | 1.66 | 0.43 | 0.43 | 0.04 | 0.13 | 0.04 | 0.22 | 0.04 | 0.26 | 0.05 | 0.28 | 0.09 | 0.65 | 0.08 | F3IV |
| 8          | G284.0110-00.1208 | 10231333-5726356 | 12.46 | 0.04 | 1.54 | 0.43 | 0.33 | 0.05 | 0.06 | 0.05 | 0.20 | 0.05 | 0.14 | 0.05 | 0.18 | 0.09 | 0.49 | 0.07 | F3IV |
| 9          | G284.0305-00.1750 | 10245800-5741272 | 11.57 | 0.04 | 0.95 | 0.43 | 0.43 | 0.04 | 0.13 | 0.04 | 0.22 | 0.04 | 0.26 | 0.05 | 0.28 | 0.09 | 0.65 | 0.08 | F3IV |

References. — (1) Reference ID # for this paper; (2) GLIMPSE Catalog ID which is in Galactic coordinates; (3) 2MASS Catalog ID; (4) 2MASS K magnitude; (5) 1σ uncertainty for K magnitude; (6) Guide Star Catalog 2.2 V - 2MASS K; (7) 1σ uncertainty for V-K; (8) 2MASS J - 2MASS K; (9) 1σ uncertainty for J-K; (10) 2MASS H - 2MASS K; (11) 1σ uncertainty for H-K; (12) 2MASS K - IRAC [3.6] using zero-points from (Cohen et al. 2003) used in all colors; (13) 1σ uncertainty for K-[3.6]; (14) 2MASS K - IRAC [4.5]; (15) 1σ uncertainty for K-[4.5]; (16) 2MASS K - IRAC [5.8]; (17) 1σ uncertainty for K-[5.8]; (18) 2MASS K - IRAC [8.0]; (19) 1σ uncertainty for K-[8.0]; (20) Spectral type
| ID          | 2MASS ID         | K    | σK   | V-K  | σV-K | J-K  | σJ-K | H-K  | σH-K | K-[3.6] | σK-[3.6] | K-[4.5] | σK-[4.5] | K-[5.8] | σK-[5.8] | K-[8.0] | σK-[8.0] | Spec.     | E(K-8) |
|------------|------------------|------|------|------|------|------|------|------|------|--------|---------|--------|---------|--------|---------|--------|---------|-----------|-------|
| (1)        | (2)              | (3)  | (4)  | (5)  | (6)  | (7)  | (8)  | (9)  | (10) | (11)   | (12)    | (13)   | (14)    | (15)   | (16)    | (17)   | (18)    | (19)      | (20)   |
| 19         | G283.9403-00.2636 | 10221243-5731324 | 9.81 | 0.02 | 0.52 | 0.05 | 0.07 | 0.03 | 0.06 | 0.03   | 0.51    | 0.03   | 0.71    | 0.03   | 0.92    | 0.03   | 1.32    | 0.02 | B2V(weak Be) | 1.43 |
| 20         | G284.1728-00.2039 | 10235451-5736004 | 10.63 | 0.02 | 0.49 | 0.06 | 0.08 | 0.03 | 0.00 | 0.03   | 0.54    | 0.03   | 0.61    | 0.03   | 0.73    | 0.05   | 1.03    | 0.09 | B1V(weak Be) | 1.08 |
| 21         | G284.1277-00.5835 | 10220574-5753460 | 10.60 | 0.02 | 3.91 | 0.49 | 0.39 | 0.04 | 0.11 | 0.04   | 0.15    | 0.04   | 0.22    | 0.05   | 0.29    | 0.12   | 0.60    | 0.12 | F5I1     | 0.57 |
| 22         | G284.0335-00.2091 | 10240243-5744359 | 8.65  | 0.03 | 0.84 | 0.04 | 0.16 | 0.05 | 0.40 | 0.05   | 0.75    | 0.05   | 1.50    | 0.03   | 3.84    | 0.03   | 4.08    |       |          |       |
| 23         | G284.2642-00.3156 | 10230066-5731474 | 12.74 | 0.03 | 1.68 | 0.03 | 0.58 | 0.04 | 0.38 | 0.06   | 0.44    | 0.03   | 0.70    | 0.03   | 0.90    | 0.03   | 1.24    | 0.02 | B        | 1.15 |
| 24         | G283.9567+00.1258 | 10235162-5712213 | 13.04 | 0.03 | 0.38 | 0.04 | 0.08 | 0.04 | 0.18 | 0.05   | 0.11    | 0.06   | 0.43    | 0.17   | 0.59    | 0.09   | G8II     | 0.54 |
| 25         | G283.9776+00.1738 | 10241078-5710353 | 13.03 | 0.03 | 0.39 | 0.03 | 0.07 | 0.03 | 0.09 | 0.04   | 0.10    | 0.06   | 0.45    | 0.24   | 0.63    | 0.13   | F5III    | 0.61 |
| 26         | G284.0380-00.5951 | 1020784-5759512  | 7.49  | 0.02 | 1.44 | 0.03 | 0.58 | 0.04 | 0.38 | 0.06   | 0.44    | 0.03   | 0.70    | 0.03   | 0.90    | 0.03   | 1.24    | 0.02 | B        | 1.15 |
| 27         | G283.9311-00.5360 | 10212249-5746404 | 13.39 | 0.04 | 1.80 | 0.44 | 0.54 | 0.05 | 0.21 | 0.06   | 0.15    | 0.05   | 0.12    | 0.08   | ...     | 1.00   | 1.62    | 0.20 | G2V      | 1.60 |
| 28         | G284.0107-00.1372 | 10230932-5727250 | 14.05 | 0.05 | 2.08 | 0.45 | 0.48 | 0.05 | 0.11 | 0.05   | 0.11    | 0.07   | 0.06    | 0.09   | ...     | 1.00   | 1.58    | 0.20 | F8V      | 1.53 |
| 29         | G283.9764-00.1365 | 10225656-5726169 | 13.36 | 0.04 | 0.63 | 0.02 | 0.63 | 0.05 | 0.23 | 0.05   | 0.30    | 0.06   | 0.36    | 0.07   | ...     | 1.00   | 1.09    | 0.14 | A7V      | 1.11 |
| 30         | G284.4730-00.2456 | 10253880-5747417 | 12.33 | 0.03 | 0.65 | 0.43 | 0.18 | 0.04 | 0.03 | 0.04   | 0.06    | 0.04   | 0.09    | 0.05   | 0.23    | 0.11   | 0.34    | 0.07 | A7V      | 0.36 |
| 31         | G283.9309-00.0712 | 10225509-5721302 | 12.58 | 0.03 | 1.91 | 0.44 | 0.53 | 0.04 | 0.11 | 0.17   | 0.04    | 0.01   | 0.05    | 0.24   | 0.10    | 0.44   | 0.11   | G0V      | 0.40 |
| 32         | G283.9809-00.1931 | 10224464-5730119 | 12.78 | 0.02 | 0.43 | 0.04 | 0.11 | 0.04 | 0.12 | 0.04   | 0.05    | 0.05   | 0.12    | 0.01   | 0.52    | 0.21   | F8V      | 0.52 |

References. — (1) Reference ID # for this paper; (2) GLIMPSE Catalog ID; (3) 2MASS Catalog ID; (4) 2MASS K magnitude; (5) 1σ uncertainty for K magnitude; (6) Guide Star Catalog 2.2 V - 2MASS K; (7) 1σ uncertainty for V-K; (8) 2MASS J - 2MASS K; (9) 1σ uncertainty for J-K; (10) 2MASS H - 2MASS K; (11) 1σ uncertainty for H-K; (12) 2MASS K - IRAC [3.6]; (13) 1σ uncertainty for K-[3.6]; (14) 2MASS K - IRAC [4.5]; (15) 1σ uncertainty for K-[4.5]; (16) 2MASS K - IRAC [5.8]; (17) 1σ uncertainty for K-[5.8]; (18) 2MASS K - IRAC [8.0]; (19) 1σ uncertainty for K-[8.0]; (20) Spectral type of star; (21) E(K - 8) for star.
Table 3. Derived Parameters for Candidate β Pictoris Analogs

| ID             | 2MASS ID     | Spec.  | E(K-8) | Distance | A_v     | Temp  | \( \frac{L_{IR}}{L_{**}} \) | Teff | Log g |
|----------------|--------------|--------|--------|----------|---------|-------|-----------------------------|------|-------|
| 1              | G284.3535-00.2021 10250358-5741409 A3V | 1.00 | 1068±160 | 0.00±0.07 | 385±70 | 0.044±0.0014 | 8200±4.29 |
| 2              | G284.1744-00.5141 10224039-5751461 A2V | 0.92 | 1398±210 | 0.00±0.08 | 300±37 | 0.005±0.0025 | 8200±4.29 |
| 3              | G283.8842-00.3361 10213378-5733229 B9V | 0.77 | 1938±290 | 0.00±0.00 | 582±95 | 0.001±0.0002 | 9520±4.14 |
| 4              | G284.1241-00.2429 10232673-5736249 A7V | 0.54 | 563±80 | 0.04±0.00 | 620±125 | 0.003±0.0005 | 7200±4.34 |
| 5              | G284.0185-00.1803 10230188-5729511 K0V | 0.43 | 593±90 | 0.17±0.17 | 801±56 | 0.007±0.0011 | 5250±4.49 |
| 6              | G284.0547-00.5695 10214145-5750415 B5V | 1.24 | 3073±475 | 0.47±0.47 | 450±45 | 0.013±0.0011 | 1900±4.04 |
| 7              | G284.0719-00.1637 10223641-5730435 F3IV | 0.62 | 963±140 | 0.78±0.78 | 801±30 | 0.008±0.0011 | 6440±4.34 |
| 8              | G284.0110-00.1208 10231333-5726356 F2IV | 0.46 | 918±60 | 0.62±0.62 | 838±14 | 0.007±0.0005 | 6440±4.34 |
| 9              | G284.2320-00.1670 10242577-5736016 A5V | 0.61 | 773±110 | 0.41±0.41 | 108±30 | 0.008±0.0005 | 8200±4.29 |
| 10             | G284.0658-00.3254 10224465-5738431 G0V | 0.55 | 493±75 | 0.04±0.04 | 676±125 | 0.009±0.002 | 6630±4.49 |
| 11             | G283.9773-00.3948 10215463-5739217 B8V | 0.42 | 2798±420 | 0.41±0.41 | 160±150 | 0.009±0.002 | 1900±4.04 |
| 12             | G283.9935-00.1944 10224307-5729455 G5V | 1.03 | 553±85 | 0.27±0.27 | 424±48 | 0.015±0.0025 | 5770±4.49 |
| 13             | G283.9329-00.5103 10210640-5743271 F3IV/V | 0.71 | 793±120 | 0.30±0.30 | 442±81 | 0.005±0.0015 | 6440±4.34 |
| 14             | G283.9153-00.4337 10212181-5739183 F3V | 0.93 | 1068±165 | 0.39±0.39 | 395±54 | 0.011±0.0027 | 6440±4.34 |
| 15             | G284.0478-00.1686 10233546-5701199 K7V | 0.91 | 608±65 | · · · | 654±60 | 0.030±0.0022 | 4350±4.54 |
| 16             | G284.9076-00.1997 10221550-5727151 G8IV | 0.49 | 268±40 | · · · | 723±52 | 0.006±0.0010 | 5250±4.49 |
| 17             | G284.9040-00.3687 10213333-5735348 K5V | 0.50 | 338±50 | · · · | 776±74 | 0.014±0.0029 | 4350±4.49 |
| 18             | G284.3417-00.2049 10245840-5741272 F8Ve | 1.05 | 513±75 | · · · | 560±84 | 0.010±0.0002 | 6030±4.49 |

References. — (1) Reference ID # for this paper; (2) GLIMPSE Catalog ID; (3) 2MASS Catalog ID; (4) Spectral type of star; (5) E(K – 8) for star; (6) Spectrophotometric distance; (7) Visual extinction; (8) Best fit blackbody model temperature for excess; (9) Best fit disk to star luminosity ratio; (10) Effective temperature for the adopted Kurucz model (11) Log g for the adopted Kurucz model
Fig. 1.— Color-color plots of cataloged point sources in the GLIMPSE OSV region (Westerlund 2 region). The black lines are the extinction vectors of Li & Draine (2001). The dashed vectors are the extinction laws of Indebetouw (2005) in the mid-IR. Both sets of extinction lines represent $A_V = 10$ and are offset from the stellar loci for clarity. The green pluses are $\log \frac{F_{8.0}}{F_{3.6}} \geq -0.5$ (criterion 1), the red are $\log \frac{F_K}{F_J} \geq 0.15$ (criterion 2), and the blue are $\log \frac{F_{5.8}}{F_{3.6}} \geq -0.25$ (criterion 3).
Fig. 2.— The Kurucz model spectral class versus the \((K - 8)\) color excess. The majority of stars have no significant \((K - 8)\) excess and cluster between -0.21 and 0.35 (denoted by the vertical bars), while 33 stars have an excess greater than 0.35 mag. The vertical lines denote the \(3\sigma\) dispersion from the mean of the 110 stars without excesses. The distribution shows that there is a long tail with excesses exhibited by stars of all spectral classes.
Fig. 3.— Color-color plots of stars in the GLIMPSE OSV region. The large black asterisks mark classified stars with a \((K - 8)\) excess. The triangles mark classified stars with a \((K - 8)\) excess which did not have a V-band GSC measurement. The diamonds denote spectroscopic target stars which were too faint or featureless for spectral classification. Most of the diamonds are consistent with being heavily reddened stars. The black vectors are the extinction vector of Li & Draine (2001). The dashed vectors are the extinction law of Indebetouw (2005) in the mid-IR. Both sets of extinction vectors represent \(A_V = 10\) and are offset from the stellar sequence for clarity. The solid thin line is the theoretical main-sequence, the dash-dot is the giant, and the dashed is the supergiant sequence. (De Jager, C. & Nieuwenhuijzen, H. (1987), Schmidt-Kaler, Th. (1982), Johnson, H.L. (1966))
Fig. 4.— SED of $\beta$ Pictoris using GSC, 2MASS and Backman et al. (1992) measurements. Like most of our candidate sources, $\beta$ Pictoris shows an excess at longer mid-IR wavelengths. $\beta$ Pictoris did show a small excess at 4.80 $\mu$m in Backman et al. (1992). The thick solid line is the Kurucz model ($T_{\text{eff}}$=8200 K, Log g=+4.29), the thick dashed is the Kurucz model with extinction applied, the dot-dash line is the SED of the blackbody component with $T$=223 K, and the thin line is the combination of the Kurucz model with extinction plus the SED of the disk component. The residual plots below are shown before the addition of the blackbody component. They demonstrate that at longer wavelengths $\beta$ Pictoris deviates from the model photosphere.
Fig. 5.— Plot of the Monte Carlo simulation for β Pictoris. The simulation demonstrates that temperature and fractional luminosity are well constrained to $223^{+4}_{-4}$ and fractional luminosity $0.0019^{+0.0002}_{-0.0002}$. 
Fig. 6.— Histograms of (A) derived extinction, (B) spectrophotometric distance, (C) blackbody temperature and (D) fractional luminosity for $\beta$ Pictoris using a Monte Carlo simulation.
Fig. 7.— SED of G284.3535-00.2021, one of our candidate β Pictoris analogs. The thick solid line is the Kurucz model, the dot-dash line is the SED of the disk component, and the thin line is the combination of the Kurucz model with extinction plus the SED of the disk component. The residual plots below are shown before the addition of the blackbody component. G284.3535-00.2021 shows a significant deviation from the photosphere at 8 µm.
Fig. 8.— Scatter plot of the best fit blackbody temperature versus fractional disk-to-star luminosity ration based on 2000 Monte Carlo simulations for G284.3535-00.2021. A wide range of temperatures and fractional luminosities are allowed for the given photometric measurements, but these allowed values are constrained to a narrow region of parameter space. The majority of the simulations indicate preferred disk temperatures of 315-440 K and fractional disk-to-star luminosities of 0.0033 to 0.0057 as show in the histograms in Figure 9.
Fig. 9.— Histograms of (A) derived extinction, (B) spectrophotometric distance, (C) black-body temperature and (D) fractional luminosity for G284.3535-00.2021. The distributions for the derived parameters constrain the possible values, but the dispersion is larger than in the simulations of β Pic because the models are not as tightly constrained without data longward of 8 µm.
Fig. 10.— Histograms of both temperature and fractional luminosity for the remaining 17 stars in Table 3. The reference number in the figure refers to the star ID in this paper.
Fig. 11.— Histograms of both temperature and fractional luminosity for the median values derived for the G18 stars in Table 3. Although all the stars exhibit a mid-IR excess, there is a broad range of both temperatures and fractional luminosities for sample.
Fig. 12.— Optical Spectrum of G284.2642-00.3156 with stellar hydrogen and helium lines marked. The lack of strong He I absorption lines but strong He II lines make this a very early O-star, probably an O4. The diffuse interstellar band feature at 4430 Å and 4882 Å is consistent with the high extinction ($A_V=5.6$) to this star (Herbig 1995). The [O III] emission lines reveal the presence of ionized gas near the star.
Fig. 13.— [3.6] Spitzer IRAC image showing both Westerlund 2 and the O4V((f)) star. The position of the O star is shown by a white box. Diffuse emission in this band is attributed to known PAH features.
Fig. 14.— [8.0] Spitzer IRAC image showing both Westerlund 2 and the O4V((f)) star. The position of the O-star is shown by a white box. The [8.0] image shows a circular emission ring around the star, although the star is not centered within this ring. The ring and the irregular linear feature extending to the NW from the star may trace molecular material or dust illuminated by the star. The diffuse emission is attributed to known PAH features in the [8.0] band.