THE ASTRONOMICAL JOURNAL, 124:514–518, 2002 July

M-TYPE VEGA-LIKE STARS

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Received 2001 August 10; accepted 2002 April 8

ABSTRACT

We carried out a search for M-type Vega-like stars by correlating the *IRAS* Faint Source Catalog with *Hipparcos*-selected M-type stars. Three stars with apparent *IRAS* 25 μm excess emission are shown instead to be non–IR-excess stars from ground-based 11.7 and 17.9 μm photometry. Two stars previously suggested to have Vega-like mid-IR excess are also shown to be nonexcess stars. These results imply that other suggested mid–IR-excess stars in the literature may also be false excess stars. Detection threshold bias is apparently responsible for these bogus IR excesses. Sixty micron excess emission from a previously known M-type Vega-like star (GJ 803) is identified again.

Key words: circumstellar matter — planetary systems: general — planetary systems: protoplanetary disks — stars: individual (GJ 803) — stars: late-type

1. INTRODUCTION

During the past 15 yr, about two dozen papers have been published that describe searches for stars with excess infrared (IR) emission (for recent reviews on these "Vega like" stars, see Lagrange, Backman, & Artymowicz 2000 and Zuckerman 2001). These searches employed different techniques for cross-correlating IR and stellar sources with no consistent definition of what defines an IR excess (see Song 2000 for a summary). To date, about 400 Vega-like stars have been identified. The Vega phenomenon overlaps with some very important solar system formation epochs; gas giant planet formation at $\lesssim$10 Myr and terrestrial planet formation at ~100 Myr. Thus, knowing stellar ages of Vega-like stars is essential to studying extra solar planetary system formation in detail. Consequently, there have been many efforts to estimate the ages of Vega-like stars (see Song 2000; Spangler et al. 2001; and references therein). Stellar ages can be fairly accurately and relatively easily determined for late-type stars (e.g., Song et al. 2000); however, ages of early-type stars are less reliable (Song et al. 2001a). Most of the currently known Vega-like stars are early-type because more luminous stars produce larger IR fluxes for stars with the same quantity of dust and the surveys conducted by *IRAS* were flux-limited. Thus, it is desirable to increase the known number of late-type Vega-like stars for more precise age estimates of such stars. Additional identification of late-type Vega-like stars is very useful to statistically strengthen studies such as planetary formation in different environments and dust lifetime as a function of stellar mass and luminosity (see, e.g., Song's 2001 suggestion of dichotomy of Vega-like stars). In addition, late-type Vega-like stars are excellent laboratories for studying the early evolution of our solar system.

Despite the great number of M-type stars compared to earlier types, only two with IR excesses, GJ 803 (Tsikoudi 1988) and Hen 3-600 (de La Reza et al. 1989; Jayawardhana et al. 1999), have been identified to date. Almost all previous studies (exceptions include Aumann & Probst 1991 and Odenwald 1986) searched only for far-infrared (60 μm) excess and were limited by the *IRAS* ~90% completeness sensitivity of 280 mJy in that band. *IRAS* sensitivity at 25 μm was 210 mJy, and an M0 star located 10 pc away with 200 K dust grains absorbing and emitting like blackbodies such that $L_{\rm IR}/L_{\rm star} = 1.5 \times 10^{-3}$ would have been detected by *IRAS* at 25 μm ($F_{\rm star+disk} \simeq 250$ mJy) but not at 60 μm ($F_{\rm star+disk} \simeq 100$ mJy).

A more complete survey for dust must be able to detect the stellar photosphere at high precision in order to evaluate excess emission above that level. One can do a fairly thorough disk excess assessment for stars whose photospheres were detected by *IRAS*. However, around stars whose photospheres were too faint to be detected, only unusually large disk excesses could be detected. At 60 μm, *IRAS* could detect the photosphere of an A0 star out to ~20 pc, but an M0 star only out to ~2 pc. The situation is somewhat better at 25 μm, where *IRAS* could detect the photosphere of an A0 star out to ~50 pc and an M0 photosphere out to ~5 pc. By searching the catalog only at 60 μm, previous surveys have not probed large regions of phase space where excess may exist around late-type stars.

In this study, we concentrated mainly on M-type stars and attempted to perform the most thorough search for M-type Vega-like stars to date, especially at 25 μm, based on the *IRAS* Faint Source Catalog (FSC; Moshir et al. 1992) and *Hipparcos* catalog (Perryman et al. 1997). As a check on recently reported infrared excess stars, however, we also report on the F-type star HD 2381.

2. SEARCH

Based on the *Hipparcos* catalog, we selected ~530 nearby (less than 25 pc) stars with $(B-V) + \sigma_{(B-V)} > 1.40$, where $\sigma_{(B-V)}$ is the uncertainty of $B-V$. The *Hipparcos* catalog contains almost all early M-type (M0–2) stars within 10 pc. Many IR sources in the FSC with optical stellar identifications are giant stars (Zuckerman, Kim, & Liu 1995; Odenwald 1986). Therefore, one needs luminosity class information to identify Vega-like stars. Following Silverstone (2000), we used a constraint on the absolute visual

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magnitude [$M_V > 7.5(B-V) - 5.0$] to ensure that a candidate is not a giant star whose IR-excess mechanism may be different from that of a dwarf. Six stars from our initial sample do not meet the absolute visual magnitude cut, and they are HIP 21421, 50798, 66212, 66906, 75187, and 82099. HIP 21421 and HIP 66212 are K-type giants, and the other four stars appear to be main-sequence stars with large uncertainties in $B-V$. Among the four rejected main-sequence stars, HIP 75187 is the only one detected by *IRAS* (only at 12 μm), and the measurement agrees with the flux density expected from its photosphere alone. Then, our sample stars were cross-correlated with FSC sources with a maximum allowed offset of 30″ between *Hipparcos* and *IRAS* source positions (both at epoch 1983.5 and equinox B1950.0). Only 152 stars from our initial sample have IR counterparts; among them, 96 stars were detected only at 12 μm, and 55 stars were detected at both 12 and 25 μm. GJ 803 (AU Mic) was detected at 12 and 60 μm and was the only dwarf M-type star that has been detected at the *IRAS* 60 μm band. No objects were detected at 100 μm. A previously known M-type IR-excess star, Hen 3-600 (TWA 3), is not identified in our search because it is not bright enough to be included in the *Hipparcos* catalog.

Positions given in the published *IRAS* catalog are weighted means of 12, 25, 60, and 100 μm source positions based on their signal-to-noise ratios (S/N). Sometimes, 25 and 60 μm sources are background objects far away from the stellar 12 μm sources. Thus, in IR-excess surveys, it is mandatory to check each band's source position and to confirm that source positions in each band are coincident. We checked the offsets between 12 and 25 μm positions (60 μm position also for GJ 803) by using the " LONG FSC " from IPAC at the California Institute of Technology and found that only one object (GJ 433) shows a substantial (36″) offset between the 12 and 25 μm *IRAS* sources. For comparison, a median positional uncertainty of *IRAS* FSC sources in the cross-scan direction is 20″. Offsets between the 12 and 25 μm source positions for the other stars are negligible with respect to the *IRAS* positional uncertainties.

To identify IR excesses, we performed spectral energy distribution (SED) fitting by using all known photometric data from the literature (queried through SIMBAD) including on-line 2MASS data. For GJ 413.1 and GJ 433, *JHK* magnitudes (see Table 1) were measured on 2000 November 24 (UT) with the NASA Infrared Telescope Facility (IRTF) at Mauna Kea Observatory. Since the accuracy of the photospheric flux estimation at 12 μm depends strongly on the availability of near-IR photometric data (i.e., *JHK* magnitudes), we have not carried out a SED fit to stars with only 12 μm detections, because most of these stars lack near-IR photometry. Stellar SEDs are different from that of a blackbody. Opacity sources absorb light at wavelengths with high opacities and reradiate it at wavelengths with relatively low opacities. This results in a SED very different from that of a blackbody. Therefore, we used PHOENIX NextGen synthetic stellar spectra (Hauschildt et al. 1999) instead of a blackbody SED. Among three SED fitting parameters (parallax, stellar radius, and effective temperature), *Hipparcos* parallax has been treated as constant. Stellar radius and effective temperature were estimated from the *Hipparcos* $B-V$ value by using the spectral type versus colors/$T_{\rm eff}$/radius relation of de Jager & Nieuwenhuijzen (1987).

To quantify the strength of IR excesses, we defined r, the specific IR excess, (" specific excess " hereafter) as

$$r \equiv \frac{F^{\rm IRAS}_{25\,\mu{\rm m}} - F^{\rm est}_{25\,\mu{\rm m}}}{F^{\rm est}_{25\,\mu{\rm m}}}\ , \tag{1}$$

where $F^{\rm IRAS}_{25\,\mu{\rm m}}$ and $F^{\rm est}_{25\,\mu{\rm m}}$ are the *IRAS* FSC 25 μm flux and estimated photospheric contribution at 25 μm, respectively. For GJ 803, we used $F^{\rm IRAS}_{60\,\mu{\rm m}}$ and $F^{\rm est}_{60\,\mu{\rm m}}$ to calculate its 60 μm specific excess ($r_{60\,\mu{\rm m}}$).

As shown in Figure 1, we found three stars (GJ 154, 413.1, and 433) with $r > 2.0$ based on 25 μm fluxes and a different star (GJ 803) with $r = 7.60$ based on 60 μm flux. Contrary to an expected median-specific excess value of zero for non–IR-excess stars, Figure 1 shows a median value of $\sim$0.1 that may be due to the 25 μm flux overestimation as explained in the *IRAS* Explanatory Supplement, p. III–131. All *IRAS* flux density values in Table 1 and Figures 2–3 are color-corrected using Table VI.C.6 of the *IRAS* Explanatory Supplement. For 12 and 25 μm fluxes, stellar effective temperatures were used to estimate color correction factors. However, for 60 μm fluxes, if any IR excess existed (e.g., GJ 803), then dust temperatures were used instead of stellar effective temperatures.

TABLE 1

M-Type IR-Excess Candidates

Source	Sp. Type	Dist. (pc)	Near-IR Data[a] (mag) J	H	K	*IRAS* Flux (mJy) 12 μm	25 μm	60 μm	r Value	Keck Flux (mJy) 11.7 μm	17.9 μm	Prediction[b] (mJy) 11.7 μm	17.9 μm	Excess?
GJ 154........	M0	14.6	6.67 (3)	6.03 (5)	5.85 (5)	150 ± 24	114 ± 53	<199	2.18	159 ± 13	74 ± 11	157	68	No
GJ 413.1.....	M2	10.7	7.23 (2)	6.55 (2)	6.23 (2)	141 ± 21	80 ± 20	<130	3.38	177 ± 27	43 ± 20	147	64	No
GJ 433........	M1.5	9.0	6.46 (2)	5.95 (2)	5.67 (2)	205 ± 25	108 ± 27	<101	2.28	213 ± 11	101 ± 20	214	93	No
GJ 803........	M0	9.9	...	...	...	537 ± 32	<215	273 ± 46	7.60[c]	...	...	633	275	Yes
GJ 816........	M3	13.8	7.55 (1)	6.96 (2)	6.69 (2)	...	...	...	...	93 ± 13	<55[d]	101	45	No
HD 2381	F2 V	74.2	6.99 (1)	6.86 (4)	6.74 (1)	127 ± 33	<73	<170	2.30[e]	55 ± 5	28 ± 14	55	24	No

[a] The near-IR data for GJ 154 are from Alonso, Arribas, & Martinez-Roger 1994, that for GJ 413.1 and GJ 433 are from our IRTF measurements, and that for GJ 816 and HD 2381 are from the 2MASS database.

[b] The expected photospheric flux.

[c] The 60 μm specific excess. The 25 μm value is an upper limit.

[d] This is 18.7 μm flux upper limit not the 17.9 μm.

[e] The 12 μm specific excess. The 25 μm value is an upper limit.

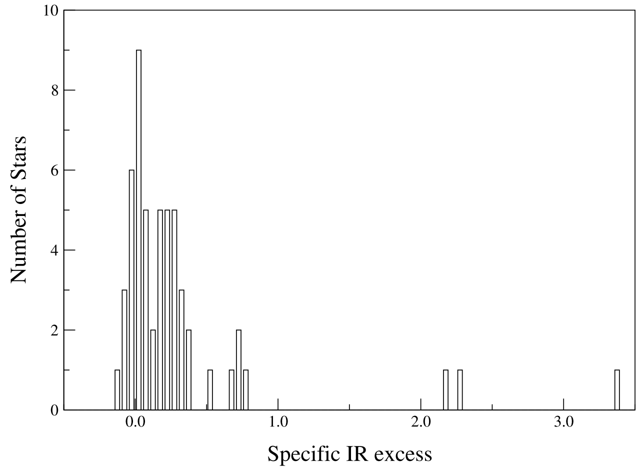

FIG. 1.—Histogram of specific IR excess ($r_{25\,\mu\mathrm{m}}$) for the 55 stars discussed in the text. The r value of GJ 803 ($r_{60\,\mu\mathrm{m}} = 7.6$) is outside of the displayed range.

3. GROUND-BASED MID-IR PHOTOMETRY

Mid-infrared imaging was performed with the facility instrument, the Long Wavelength Spectrograph (LWS; Jones & Puetter 1993), on the 10 m Keck I telescope on UT 2000 December 11 and 2001 February 4–5. During all three nights, the weather was photometric, with low water vapor optical depth. LWS uses a 128 × 128 pixel Boeing Si:As detector and has a plate scale of 0″.08 pixel^{-1}, resulting in a focal-plane field of view of 10″.24 × 10″.24. Each object was measured in filters centered at 11.7 μm (FWHM = 1.0 μm) and 17.9 μm (FWHM = 2.0 μm). Images were obtained at four positions by chopping the secondary at 2.5–5 Hz, with a throw of 10″, and nodding the telescope 10″ after ∼20 s. In basic data reduction, the images were double-differenced to remove the sky and telescope background, and bad pixels were corrected by interpolation. Throughout the nights, including just before and after each of the M star measurements, bright infrared standard stars were observed for photometric calibration. Standard-star measurements over the whole of each night were averaged, and the standard deviation in their photometry was used as an estimate of calibration uncertainty. On December 11, the uncertainty in the calibration was 5% and 6% at 11.7 and 17.9 μm, respectively. On February 4 and 5, the uncertainties were 15% at both wavelengths.

Photometry was performed in a 16 pixel (1″.3) diameter synthetic aperture on each image, and the results are reported in Table 1. For an M star of luminosity 0.1 $L_\odot$, blackbody-like grains at a thermal equilibrium temperature of 200 K will sit 0.6 AU from the star. Therefore, at a dis-

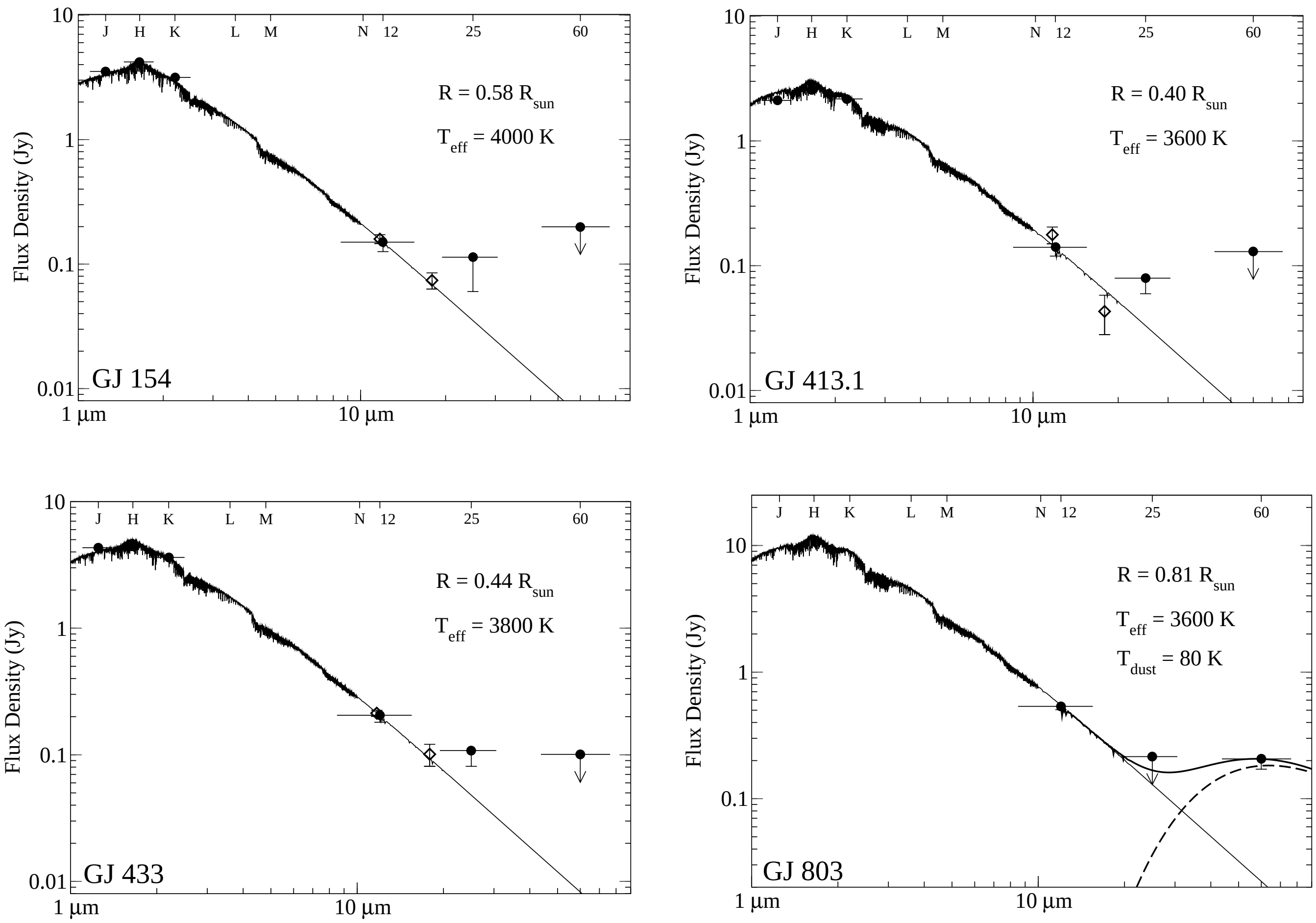

FIG. 2.—SED fits of M-type stars with tentative IR excesses identified from this study by using the *IRAS* FSC. Filled circles are *JHK* and *IRAS* data, and diamonds indicate our ground-based 11.7 and 17.9 μm fluxes. Thin solid lines are synthetic stellar spectra fit to visual and near-IR ($\lambda < 2\ \mu$m) photometry ([M/H] = 0.0 and log $g = 5.0$), and a dotted line (only for GJ 803) indicates a dust component with $T = 80$ K and $L_{\mathrm{IR}}/L_* = 6.7 \times 10^{-4}$. Wavelength and flux density scales are logarithmic. Horizontal bars across *JHK* and *IRAS* data points indicate passband widths.

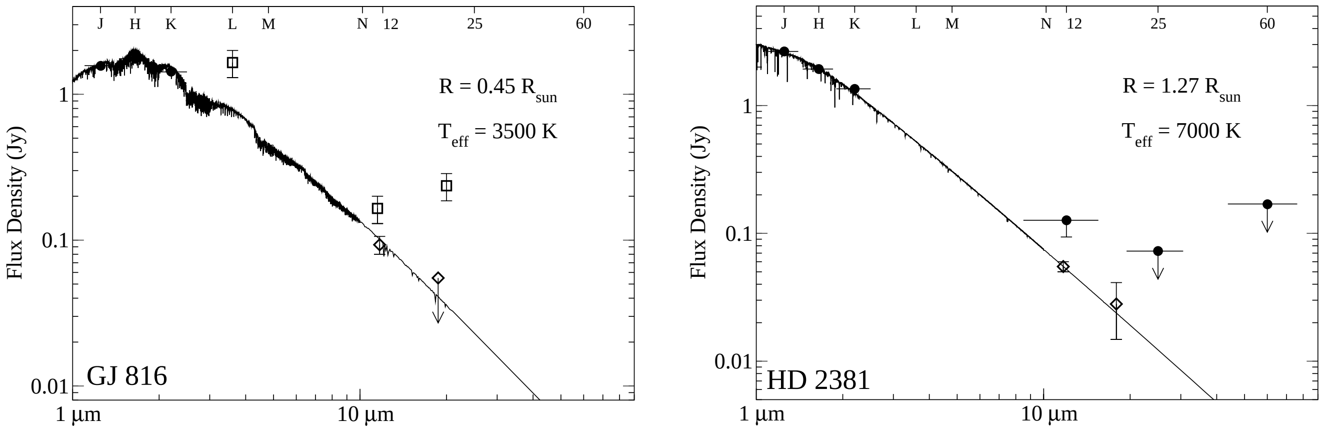

FIG. 3.—Same as Fig. 2, but for Vega-like stars from the literature. For GJ 816, open squares show *ISO* fluxes (there is no *IRAS* data), and open diamonds show LWS measurements with the Keck I telescope.

tance of 10 pc, any 12 or 18 μm excess should appear less than 0."1 in size, or spatially unresolved. It is clear from Figure 2 that the apparent 25 μm *IRAS* excesses of GJ 154, 413.1, and 433 are not real. We interpret this discord as follows:

For the faint stars under consideration whose real fluxes are near detection threshold, a downward noise fluctuation could place the 25 μm fluxes below the *IRAS* detection threshold; thus, none would display a significant 25 μm flux deficit (negative *r*). Occasional large upward noise fluctuations could boost 25 μm fluxes, so that they would be classified as IR-excess stars (positive *r*, "detection threshold bias" or "Malmquist bias"). The final configuration thus resembles our Figure 1, with some excess stars but with no significant deficit star. In fact, the *IRAS* 25 μm S/N values of all of our three false IR-excess stars are $\sim$4, which is the *IRAS* threshold value.

4. STATISTICAL SIGNIFICANCE OF IR EXCESS

Recently, Fajardo-Acosta et al. (1999) and Fajardo-Acosta, Beichman, & Cutri (2000) suggested that certain stars possess excess emission as measured by *IRAS* or *Infrared Space Observatory* (*ISO*). We checked IR excesses at GJ 816 and HD 2381 with 11.7 and 17.9 μm (18.7 μm for GJ 816) Keck photometry. Apparent excesses for both stars turned out to be false positives (Fig. 3). GJ 816 is not an *IRAS* FSC source and Fajardo-Acosta et al. (1999) used *ISO* data. An incorrect *ISO* flux calibration (for GJ 816) and Malmquist bias (for HD 2381) similar to our three false IR-excess stars may be responsible for these apparent excesses.

An occasional large upward noise fluctuation (e.g., $2\,\sigma \approx 2\%$ probability) does not significantly influence stars with high S/N; however, it can significantly affect stars with low S/N data. For our initial 152 *IRAS* sources, we expect $\sim$3 to have flux overestimates $\geq 2\,\sigma$, in apparent agreement with what we have found. Based on this fact, some suggested Vega-like stars—generally identified through huge surveys often encompassing thousands of input stars—could also be non–IR-excess stars. Thus, we suggest the following criteria for bona fide Vega-like stars: (1) high S/N not subject to a Malmquist bias, (2) low S/N detections at two or more wavelengths, or (3) ground and/or space-based confirmation (e.g., Silverstone 2000 and this study) with higher sensitivity and better spatial resolution than *IRAS*.

5. SUMMARY AND DISCUSSION

We have performed a search for IR-excess emission among M-type stars by correlating the *IRAS* Faint Source Catalog with *Hipparcos*-selected late-type stars. Besides the previously known Vega-like star (GJ 803), three tentative excess stars were identified, but these excesses turned out to be false based on our ground-based mid-IR photometry. Detection threshold bias (Malmquist bias) is thought to be responsible for these bogus *IRAS* IR excesses. Two other stars (GJ 816 and HD 2381), suggested to be Vega-like in the literature, are also shown to be non–IR-excess stars. In future studies, one should be aware that some Vega-like stars reported in the literature with low S/N values may be non–IR-excess stars as well. This is likely to be the case for most stars listed by Fajardo-Acosta et al. (2000).

GJ 803 and Hen 3-600 show strong 60 μm excesses; they are the only unambiguously identified M-type dwarf stars with IR excesses. This could be due to the extreme youth of GJ 803 (12 Myr; Zuckerman et al. 2001) and Hen 3-600 (8–10 Myr; Webb et al. 1999). Song et al. (2001b) have found two very young ($\sim$12 Myr) late-type stars (HIP 23309, M0 and HIP 29964, K6) comoving with β Pictoris. Even if one assumed that these two *Hipparcos* stars have the same fractional IR luminosity as β Pictoris ($L_{\rm IR}/L_{\rm star} \sim 10^{-3}$), their corresponding 60 μm fluxes (less than 80 and less than 40 mJy, respectively) are below the *IRAS* detection threshold. This is true for late-type stars with β Pic–like excess in nearby young stellar groups, i.e., TW Hya Association. These stars would be excellent targets for future IR-excess surveys by SOFIA or *SIRTF*.

We are grateful to Michael Schwartz for assistance obtaining *JHK* data for GJ 413.1 and GJ 433 and to M. Jura for helpful discussion and assistance with a Keck observation. We also thank an anonymous referee for suggestions that clarified the paper. This research was supported by the UCLA Center for Astrobiology and by NASA. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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