

NEW DEBRIS-DISK CANDIDATES: 24 MICRON STELLAR EXCESSES AT 100 MILLION YEARS

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Received 2004 March 31; accepted 2004 May 21

ABSTRACT

Sixty-three members of the 100 Myr old open cluster M47 (NGC 2422) have been detected at 24 μm with the *Spitzer Space Telescope*. The Be star V 378 Pup shows an excess both in the near-infrared and at 24 μm ($K - [24] = 2.4$ mag), probably due to free-free emission from the gaseous envelope. Seven other early-type stars show smaller excesses, $K - [24] = 0.6$ – 0.9 . Among late-type stars, two show large excesses: P922, a K1 V star with $K - [24] = 1.08 \pm 0.11$, and P1121, an F9 V star with $K - [24] = 3.72 \pm 0.02$. P1121 is the first known main-sequence star showing an excess comparable to that of β Pic, which may indicate the presence of an exceptionally massive debris disk. It is possible that a major planetesimal collision has occurred in this system, consistent with the few hundred Myr timescales estimated for the clearing of the solar system.

Subject headings: infrared: stars — open clusters and associations: individual (M47) — planetary systems: protoplanetary disks

1. INTRODUCTION

A knowledge of circumstellar disk evolution is crucial to understanding the planet formation process. The current paradigm predicts that optically thick accretion disks left over from star formation should dissipate as material is accreted, photoevaporated, or driven out of the system, leaving a remnant, or debris disk, formed by collisions between large bodies in a nascent planetary system (Hollenbach et al. 2000; Wyatt & Dent 2002). Studies of how these circumstellar debris disks evolve in the planet-forming zone from 1 to 10 AU, where the disk emission emerges in the mid- and far-infrared, have been limited by the sensitivity of the previous space-based infrared missions, *IRAS* and the *Infrared Space Observatory (ISO)*. The small number of F and A stars within their reach has undermined attempts to determine the frequency of excess emission. Claims of decreasing amounts of excess emission with age (Spangler et al. 2001) or an upper limit to the age of stars with debris disks (Habing et al. 2001) have been disputed by others who question the signal-to-noise ratio (S/N) of the excesses in question and/or the reliability of age estimates for nearby field stars (Decin et al. 2003).

The solution to this problem is to survey for debris disks around stars in young clusters of reliable and disparate ages. The high sensitivity of the *Spitzer Space Telescope* Multiband Imaging Photometer for *Spitzer* (MIPS) instrument at last puts this goal within reach for nearby young clusters. The use of M47, a young Galactic open cluster, as a calibration target during the *Spitzer* in-orbit checkout has provided an early opportunity to perform such a survey.

M47 (NGC 2422) is a reasonably compact (core radius 30'; Barbera et al. 2002) cluster of several hundred stars

(Ishukhamedov 1967; Mermilliod 1986; Prisinzano et al. 2003) at Galactic latitude 3° and distance around 450 pc (see discussion in § 3). Its age of 80 ± 20 Myr (Rojo Arellano et al. 1997; van Rensbergen 1978) is approximately the same as that of the Pleiades. Stromgren photometry of M47 indicates that its metallicity is also similar to that of the Pleiades and α Per clusters (Nissen 1988). Despite its proximity to the Galactic plane, M47 has a small measured reddening of $E(B - V) = 0.05$ – 0.07 (Shobbrook 1984; Nissen 1988).

2. NEW OBSERVATIONS

2.1. *Spitzer* Measurements

A region around M47 was observed with MIPS (Rieke et al. 2004) as a verification of the scan-map parameters during the in-orbit checkout period (*Spitzer* AOR 0007427328). The sky coverage is nonuniform: the effective exposure time varies over the combined $20' \times 60'$ map, from a minimum of 100 s at the edges to a maximum of about 600 s in the central $\sim 5' \times 60'$ strip. The data were reduced using the instrument team Data Analysis Tool (Gordon et al. 2004). The 24 μm mosaic is shown in Figure 1 (Plate 1). It is oversampled by a factor of 2, i.e., the pixel size is $1''.27$. The sky coverage was not optimized for the 70 μm array, and only a few (possibly extragalactic) sources were detected at this wavelength. Thus, all our analysis has focused on the 24 μm data.

Aperture photometry was performed using the DAOPHOT package (Stetson 1987). The signal aperture radius and inner and outer sky radii were set at 3.5, 9, and 18 pixels ($4''.5$, $11''.5$, and $23''$), respectively. A 0.73 mag aperture correction was applied to the measured values after examining the trend of the signal with aperture size on well-isolated stars and in synthetic images. Final magnitudes were put on a scale in which 0 mag at 24 μm is at 7.3 Jy. A total of 1093 objects was detected with $[24] < 12.0$ (0.12 mJy) and $S/N > 5$.

2.2. Optical Spectroscopy

For the three possible M47 members with the largest $K - [24]$ excesses (P1121, P369, and P922; § 4.2), optical spectra were obtained for us by J. Liebert in 2004 February using the

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blue channel of the 6.5 m MMT spectrograph. With the 1" slit, the resolution was 3.6 Å, and the wavelength coverage was 3640–6790 Å. Exposure times were 4, 4, and 5 minutes for P1121 ($V = 12.7$), P922 ($V = 14.5$), and P369 ($V = 16.2$), respectively, at air mass 1.8.

3. CLUSTER MEMBERSHIP AND *SPITZER* DETECTIONS

To interpret our results, we need to determine which 24 μm sources are members of the cluster. Our first test for membership is the color-magnitude diagram. To construct such a diagram, we need to determine the cluster distance. A distance of 497_{-88}^{+135} pc is indicated by four B stars with *Hipparcos* parallaxes (Robichon et al. 1999). Prisinzano et al. (2003) showed that the V versus $V - I$ diagram is consistent with this distance and an age of 100 Myr. Estimates from Strömgren photometry include Shobbrook (1984), 400 ± 10 pc (28 B–A stars); Nissen (1988), 425 pc (11 F stars); and Rojo Arellano et al. (1997), 470 ± 5 pc (average) and 400 ± 100 pc (median) (36 B–F stars). We adopt a distance of 450 pc and $E(B - V) = 0.07$. Because the Prisinzano et al. list of cluster members is incomplete above $3.5 M_{\odot}$, we added 11 bright stars near the cluster turnoff, taken from Robichon et al. (1999) and Rojo Arellano et al. (1997). Our photometrically selected sample of M47 members detected at 24 μm then consists of 66 objects (Fig. 1).

We confirmed probable membership for 63 of these 66 stars by proper-motion analysis. The UCAC2 (Zacharias et al. 2003), Astrographic Catalogue + Tycho (ACT; Urban et al. 1998), All-sky Compiled Catalogue (ACC; Kharchenko 2001), and Tycho (Hog et al. 2000) catalogs provided data for all the possible cluster members except P369 (which is relatively faint). Only P1218 is ruled out as a probable member, but P1078 has large errors in its proper motion and its status is unclear. All the remaining stars have appropriate proper motions for cluster membership: $\langle \mu_{\alpha} \cos \delta \rangle = -7.5 \pm 3.4$ mas yr $^{-1}$ and $\langle \mu_{\delta} \rangle = 1.9 \pm 2.3$ mas yr $^{-1}$.

We detected at 24 μm all M47 members lying within the boundaries of our mosaic and brighter than $V = 12$ mag (spectral type \sim F5, $1.5 M_{\odot}$) and a few as late as \sim K. Accurate astrometry for the cluster members is available from both Prisinzano et al. (2003), who quote errors of $0''.24$, and 2MASS, with typical errors less than $0''.1$. At 24 μm , *Spitzer* positions are accurate to $\sim 1''$, but the dominant term is an offset in the scan direction that remains fixed for a campaign. If we take this offset out, the positional agreement between cluster members and 24 μm counterparts is better than $0''.5$. The total probability of even one chance coincidence between a random 24 μm source and any cluster member whose photospheric flux is above our detection limit (0.12 mJy) is about $P = \{\pi(0''.5)^2 / [20' \times 60' \times (60'')^2]\} \times 1093 \times 63 = 1.3\%$. For objects brighter than 1 mJy at 24 μm , the probability of such a coincidence is less than 0.25% (using 195 instead of 1093). Thus, it is unlikely that there are any chance identifications for the brighter sources. Figure 2 shows $J - H$ versus $K - [24]$ for these stars.

4. DISCUSSION

The histogram of $K - [24]$ colors for the majority of M47 stars can be described by a Gaussian centered at $K - [24] = 0.11$ mag, with FWHM of 0.26 mag ($\sigma = 0.11$ mag). At these long wavelengths, for pure photospheric emission one expects $K - [24] = 0$, virtually independent of spectral type. Our distribution is shifted by +0.11 mag relative to this value;

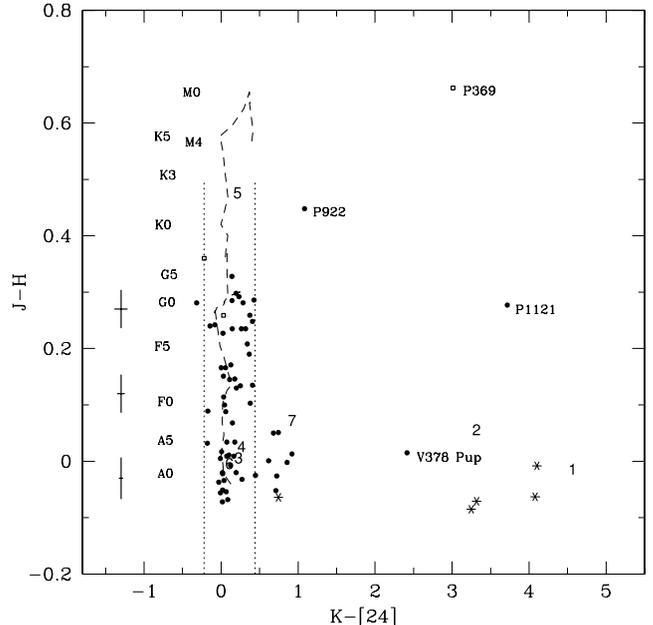


FIG. 2.—IR color-color diagram of M47 in comparison with Pleiades and field debris-disk stars. *Filled circles*, M47 members; *squares*, membership uncertain because of lack of proper-motion information; *asterisks*, Pleiades stars detected by *IRAS*; 1, HR 4796A (A0 V, 10 Myr); 2, β Pic (A3 V, 12 Myr); 3, Fomalhaut (A3 V, 220 Myr); 4, β Leo (A3 V, 240 Myr); 5, ϵ Eri (K2 V, 330 Myr); 6, Vega (A0 V, 350 Myr); 7, ζ Lep (A2nn, 370 Myr); *dashed line*, locus of main-sequence stars converted from $K - [12]$ colors in Kenyon & Hartmann (1995) by assuming $[24] = [12] + 0.08$, in which 0.08 arises because of *IRAS* color corrections; and *dotted lines*, adopted 3σ boundaries on non-excess stars. The crosses on the left represent typical error bars on M47 photometry as a function of $J - H$ (or brightness for main-sequence stars). Sources of photometry: *JHK - 2MASS* and Ducati (2002), $[24] - \text{MIPS}$ for M47, and *IRAS* [25] for the rest of the stars.

however, the offset is within the systematic error of our photometry (~ 0.10 mag, arising from uncertainties in the absolute calibration [up to 10%] and in the aperture correction), and the scatter is of the order of the random error of our photometry (0.03–0.08 mag). We therefore define excess stars as those lying redward of $(K - [24])_{\text{excess}} = 0.11 + 3\sigma = 0.44$ mag. The majority of M47 stars (55 out of 66) have 24 μm fluxes consistent with a pure photospheric origin or, at most, a small excess. The remaining stars form two groups: early-type stars with $0.6 < K - [24] < 2.5$ and three late-type stars with extreme excesses $K - [24] > 1$.

4.1. Early-Type Stars

Table 1 lists the parameters of eight M47 hot stars with 24 μm excess (out of 33 total having $J - H < 0.1$, which is characteristic of A–B stars). The most extreme one—V378 Pup (HIP 36981)—is a blue straggler and emission-line star, the only star in our sample that also shows a NIR excess (Dougherty & Taylor 1994). The incidence of substantial 24 μm excesses is large: 24% of the early-type stars have excesses greater than 0.4 mag. All of these stars are brighter than 1 mJy, so the possibility of a chance coincidence with another source is very small.

It has been known since *IRAS* (Waters et al. 1987; Cohen et al. 1987) that the fraction of stars with infrared excesses in the field is the highest among B and M stars. This result is consistent with the high incidence of excesses among the early-type stars in M47. In the case of emission-line stars, the excess is explained by free-free processes in the extended gaseous

TABLE 1
24 μm EXCESS STARS IN M47

Name	Prisinzano Number ^a	Spectral Type ^b	M_V^c	$J-H$	$K-[24]$	F_{24} (mJy)
HIP 36981.....	...	B2–B5 Ven	–2.61	0.02	2.42	558.89 ± 0.51
HIP 36967.....	...	B5–B9 Vn	–0.33	–0.05	0.71	8.86 ± 0.05
HD 60995.....	...	B8–B9 V	0.38	–0.03	0.72	5.19 ± 0.05
2MASS 07371449–1425179.....	1152	...	1.73	0.00	0.62	1.58 ± 0.03
BD –14°2028.....	1155	A2p	2.07	0.01	0.92	1.67 ± 0.02
2MASS 07362205–1430283.....	1173	...	2.13	–0.00	0.86	1.55 ± 0.02
2MASS 07365524–1433176.....	1172	...	2.42	0.05	0.68	1.13 ± 0.03
2MASS 07370687–1431348.....	1182	...	2.75	0.05	0.74	1.14 ± 0.03
2MASS 07354269–1450422.....	1121	F9 IV/V	4.40	0.28	3.72	7.31 ± 0.03
2MASS 07364576–1434348.....	922	K1 V	6.27	0.45	1.08	0.23 ± 0.02
2MASS 07372200–1424262.....	369 ^d	K0 III/IV	...	0.66	3.01	0.94 ± 0.03

^a Numbering sequence from Table 4 of Prisinzano et al. (2003).

^b From the literature (VizieR; Mermilliod 2004; Hartoog 1976; Dworetzky 1975), except for late types (this work).

^c Assuming a distance of 450 pc.

^d Our spectrum indicates this is not a cluster member.

envelopes/disks (Chokshi & Cohen 1987; Yudin 2001). The nature of the excess in non-emission-line stars is not well established: dust condensed after mass-loss episodes, dust from interstellar cirrus, and dust from circumstellar disks may all contribute (Kalas et al. 2002).

The Pleiades provide a natural comparison with M47. We identified probable Pleiades members by searching for stars within 1.5° of R.A. = $03^{\text{h}}47^{\text{m}}00^{\text{s}}$ and decl. = $+24^\circ07'00''$ (J2000.0) and with proper motions within 7 mas yr^{-1} of 17.9 and $-43.2 \text{ mas yr}^{-1}$, respectively, in right ascension and declination. We used the *IRAS* Faint Source Catalog (FSC) and Point Source Catalog (PSC) to identify infrared excesses in these stars. Our preliminary analysis of Pleiades *Spitzer* data shows that all the possible excess stars we found in this manner are surrounded by 0.5 – $1'$ extended halos that contaminate the *IRAS* measurements. Since the surface brightness from the cirrus between M47 stars is an order of magnitude less than in the Pleiades, we doubt that such halos exist around M47 stars. In addition, at the distance of M47 such halos would be resolved by the MIPS $6''$ beam—contrary to our observations (see Fig. 1). This shows the importance of M47 as a 100 Myr benchmark in disk evolution, since interpretation of Pleiades FIR data may be severely complicated by cirrus emission.

4.2. Late-Type Stars

As one moves to later spectral types, the Vega phenomenon becomes very rare at wavelengths of $25 \mu\text{m}$ and shorter. For example, Oudmaijer et al. (1992) list 462 stars with possible excesses in the *IRAS* catalog. If we take dwarf stars later than F3 and earlier than K7, brighter than $V = 8$, and at absolute Galactic latitude greater than 10° (to avoid confusion with Galactic emission), then there are no stars with candidate excesses greater than 1.5 mag at $25 \mu\text{m}$. Mannings & Barlow (1998) report a similar study, with similar results. These studies searched to the full depth of the Smithsonian Astrophysical Observatory star catalog, making chance associations a possibility. As a more stringent test, we took a complete sample of F and G dwarfs selected to have V magnitudes that would predict photospheric fluxes of 0.5 Jy or brighter at $25 \mu\text{m}$ (and thus likely to be measured well by *IRAS*). This limit was set at $V = 4$ for F0–F4, $V = 4.5$ for F5–F8, and $V = 5$ for F9–G8. For these stars, we searched the *IRAS* PSC

for high-quality measurements and, if no detection was reported there, checked whether the star was listed in the FSC. Of a total of 59 stars with good *IRAS* measurements, none had an excess greater than 0.3 mag in $[12] - [25]$. Similarly, Backman & Paresce (1993) found only two F or G dwarfs in the Bright Star Catalog (which goes to $V \sim 6.5$) with moderate ($\sim 0.5 \text{ mag}$) $25 \mu\text{m}$ excesses (HR 506 and HR 818), and most recently, Laureijs et al. (2002) found one K dwarf (HD 191408) with an excess of 0.5 mag in their 25 pc volume-limited survey.

Therefore, our discovery of three late-type M47 stars with excesses $K - [24] = 1$ – 4 mag , P1121, P922, and P369, is very surprising. To clarify their nature, we obtained the optical spectra of these stars, shown in Figure 3. We used spectral

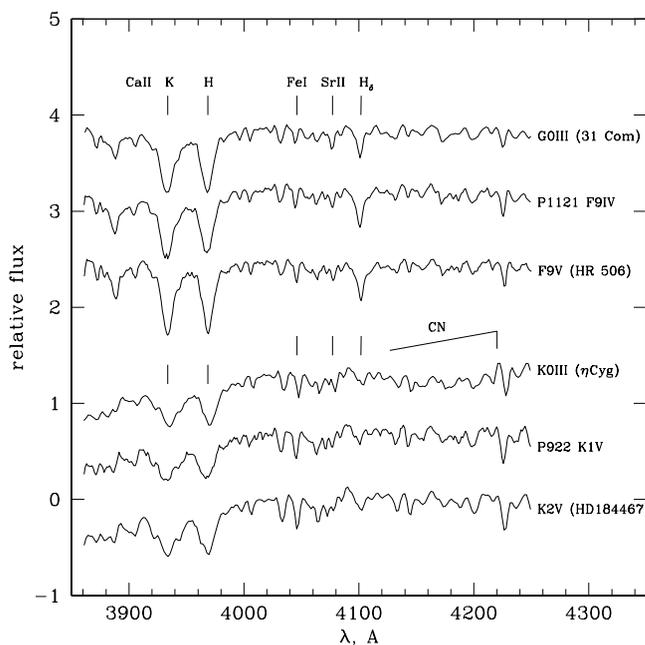


FIG. 3.—Portions of MMT spectra of P1121 and P922 in comparison with spectral standards (taken from NStars database). Sr II, as well as CN depression, is stronger than the neighboring Fe I line in giants and weaker than that in dwarfs. Weak emission in the cores of Ca II lines is seen in P1121 and P922, confirming a young age for these stars.

standards from the NStars database⁵ to classify our spectra. P369 turned out to be a reddened ($A_V \approx 1.0$ mag) K0 III–IV, slightly metal-poor star, with radial velocity $\sim +100$ km s⁻¹. It is also the only member candidate without a confirming proper-motion measurement. Thus, we believe it is a background giant. On the other hand, P922 and P1121 have radial velocities consistent with cluster membership. Their spectral types are K1.5 V and F9 IV–V, respectively, as expected from their positions on the cluster color-magnitude diagram. Both show signs of moderate chromospheric activity in Ca II K and H lines (level “k” on the scale of Gray et al. 2003), which is a bit higher than observed in 800 Myr old Hyades stars (R. O. Gray 2004, private communication). No emission is seen in H α , but slight infilling is present in H β for P1121. In conclusion, P922 and P1121 have spectral signatures of young main-sequence stars consistent with being M47 members (in addition to their proper motions and photometric characteristics).

P922 is close to the 24 μ m detection limit, and its photosphere would be below that limit, so the probability of a chance coincidence of an unrelated source with some cluster member to produce a similar “system” is $\sim 8\%$. Although P922 is only slightly below the photospheric detection limit, in this calculation we have included all known cluster members within the *Spitzer* image (~ 380). Therefore, a chance coincidence is possible but not highly likely. P922 possesses an excess at 24 μ m similar to the extreme debris-disk stars such as ζ Lep (A2 Vann, 370 Myr).

P1121 is an exceptionally interesting object. All the indicators (photometry, spectral type, proper motion, and radial velocity) place it within the cluster. Its image (Fig.1) is pointlike with no indication of extended emission in its vi-

cinity. It is 7 mJy at 24 μ m, and it is above our photospheric detection limit, so the probability of any chance association of a source this bright (25 out of 1093 total) with a cluster member is only $\sim 0.03\%$. If it is bright at longer wavelengths, it might have a disk as massive as seen in β Pic! It is also possible that it is surrounded by a less massive disk lying much closer to the star than is typical. At the age of P1121, Poynting-Robertson drag should have cleared out most of a thick, primordial disk. It is more likely the disk has been renewed by planetesimal collisions. This possibility is particularly interesting given the arguments that the solar system went through a phase of disk clearing, planet building, and violent planetesimal collisions for its first few hundred Myr (Hartmann et al. 2000).

5. CONCLUSIONS

We find substantial infrared excesses at 24 μ m in 10 stars that are members of the 100 Myr old cluster M47. The most interesting example is P1121, which is of spectral type F9 IV–V yet has $K - [24] \sim 3.7$. If this excess is due to a debris disk, it likely has a large mass and is a very rare object, judging from *IRAS* and *ISO* observations of the debris-disk phenomenon.

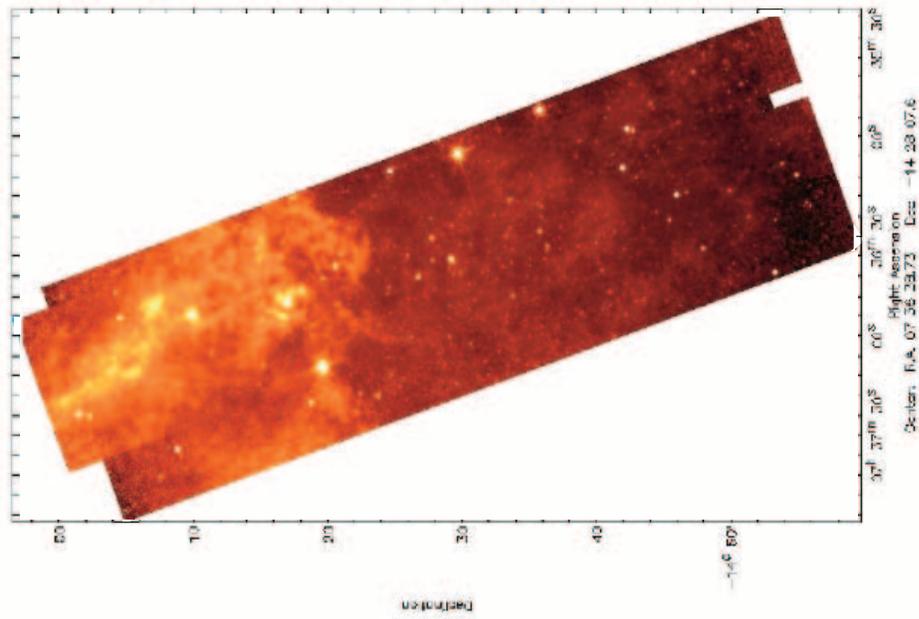
We are grateful to Jim Liebert and Kurtis Williams for obtaining spectra of the IR-excess stars, Richard Gray and Chris Corbally for help with spectral classification, Eric Mamajek for useful discussions, and to the anonymous referees for useful comments. This work is based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407. Support for this work was provided by NASA through contract 960785 issued by JPL/Caltech.

⁵ See <http://stellar.phys.appstate.edu>.

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MIPS image of M47 at 24 μ m



Excess vs. non-excess stars:

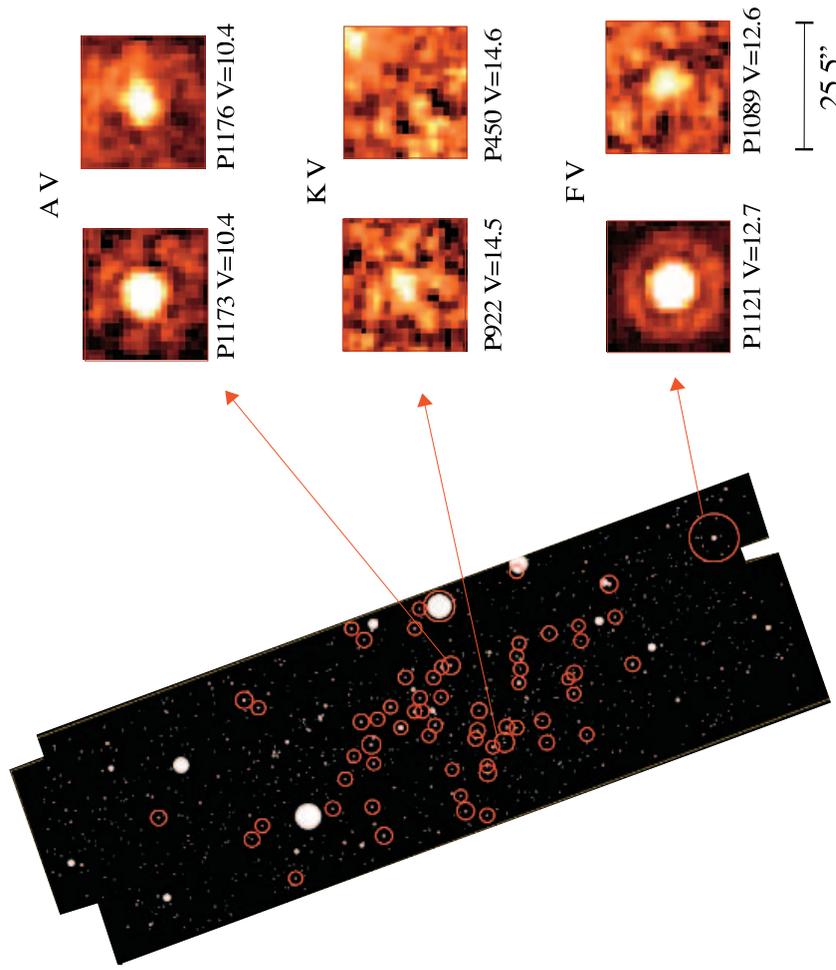


FIG. 1.—*Left*: M47 mosaic. *Middle*: Sources detected at 24 μ m. Red circles represent 24 μ m excess in M47 members (size $\sim K - [24]$). *Right*: Magnified images of some excess stars (*left column*, arrows pointing to the position on the map) compared to similar magnitude $V, B - V$ nonexcess stars (*right column*).