A POINT-SOURCE SURVEY OF M31 WITH THE SPITZER SPACE TELESCOPE

JEREMY MOULD
School of Physics, University of Melbourne, Parkville, VIC 3010, Australia; jmould@ph.unimelb.edu.au

PAULINE BARMBY
Department of Physics and Astronomy, University of Western Ontario, 1151 Richmond Street, London, ON N6A 3K7, Canada

KARL GORDON
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; kgordon@stsci.edu

S. P. WILLNER AND M. L. N. ASHBY
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; willner@cfa.harvard.edu

R. D. GEHRZ, ROBERTA HUMPHREYS, AND CHARLES E. WOODWARD
Department of Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455; gehrz@astro.umn.edu, roberta@astro.umn.edu, chelsea@astro.umn.edu

Received 2008 May 15; accepted 2008 July 2

ABSTRACT

We explore the stellar population of M31 in a Spitzer Space Telescope survey utilizing IRAC and MIPS observations. Red supergiants are the brightest objects seen in the infrared; they are a prominent evolutionary phase. Due to their circumstellar envelopes, many of these radiate the bulk of their luminosity at IRAC wavelengths and do not stand out in the near-infrared or optically. Going fainter, we see large numbers of luminous asymptotic giant branch stars (AGB), many of which are known long-period variables. Relative to M33 the AGB carbon star population of M31 appears sparse, but this needs to be spectroscopically confirmed.

Subject headings: galaxies: individual (M31) — galaxies: stellar content

Online material: color figures, machine-readable tables

1. INTRODUCTION

The disk and bulge of M31 were first resolved into stars by Hubble (1936) and Baade (1944), respectively. Since then, many optical surveys have been carried out, including those of Hubble & Sandage (1953), Baade & Swope (1963), Hodge (1981), Berkhuysen et al. (1988), Magner et al. (1992), Mochejska et al. (2001), and Massey et al. (2006). More recent papers that included spectra and optical and near-infrared photometry of individual stars are Humphreys (1979), Humphreys et al. (1988, 1990), Herrero et al. (1994), and Massey (1998). Near-infrared point-source photometry of M31 has been hampered by the lack of large-format detectors; for example, the recent work of Olsen et al. (2006) covers only a small portion of M31. The Two Micron All Sky Survey (2MASS) Large Galaxy Atlas (Jarrett et al. 2003) presented integrated photometry of M31, but no galaxy-wide assessment of the M31 point-source population has been published.

Spitzer Space Telescope characterization of the point-source population of other Local Group galaxies includes the Large Magellanic Cloud (LMC; Blum et al. 2006), M33 (Verley et al. 2007; McQuinn et al. 2007), and NGC 6822 (Cannon et al. 2006). Other Local Group dwarfs studied include IC 1613 and the WLM galaxy (Jackson et al. 2007a, 2007b, 2006). The Andromeda galaxy, M31, presents a unique opportunity to study stellar evolution at a chemical composition similar to that of the Milky Way. The red giant branch (RGB) was resolved in V and I by Mould & Kristian (1986), and the brightest evolved stars have been studied by Massey (1998). However, an infrared survey of point sources in M31 has awaited the arrival of the Spitzer Space Telescope (Werner et al. 2004; Gehrz et al. 2007) and 2MASS (Jarrett et al. 2003).

In the mid-infrared, integrated measurements of M31 have been made by IRAS (Habing et al. 1984; Xu & Helou 1996), COBE DIRBE (Odenwald et al. 1998), MSX (Kraemer et al. 2002), and Spitzer (Gordon et al. 2006; Barmby et al. 2006). With the aim of reaching stars with the most significant mass-loss rates, this paper presents a point-source survey with the Infrared Array Camera (IRAC; Fazio et al. 2004) and Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) cameras. We also utilize the 2MASS survey in order to include shorter wavelengths. We present extensive tables, giving positions of the sources we identify, to enable follow-up of these observations.

2. IRAC SURVEY

The IRAC data and reduction are described in Barmby et al. (2006). Briefly, the central $1.6\times0.4$ of M31 was imaged to a depth of six 12 s frames per position, and the outer area to a size of $3.7\times1.6$ by four 30 s frames per position. The survey was part of the Spitzer Cycle 3 program (program identification 3126). The data analyzed here were produced by version 14 of the Spitzer Science Center (SSC) pipeline; compared to the version 11 and 12 data used by Barmby et al. (2006), the newer version is expected to have more accurate pointing refinement for the individual frames. The 3000 individual frames per channel were combined with the MOPEX software to create mosaics with a pixel scale of 0.86, subsampling the native IRAC pixel scale by a factor of $\sqrt{2}$ to better sample the point-spread function (FWHM $\sim 1.9$).
The saturation limits given in the IRAC Data Handbook\(^i\) correspond to Vega magnitudes of \((9.9, 9.3, 6.7, 6.8)\) for 12 s frames and \((10.8, 10.4, 7.7, 7.8)\) for 30 s frames for the Spitzer 3.6, 4.5, 5.8, and \(8\) \(\mu\)m bands, respectively. The sensitivity can be estimated using the SSC Performance Estimation Tool\(^2\); assuming a medium background, the 5 \(\sigma\) point-source detection limits correspond to Vega magnitudes of \((19.0, 18.0, 15.6, 14.9)\) for six 12 s frames and \((19.6, 18.5, 16.0, 15.2)\) for four 30 s frames. However, point-source photometry in the vicinity of M31 is affected by crowding and at longer wavelengths by the diffuse interstellar medium, and these values are presented as a guide only.

The IRAC flat fields are derived from observations of the zodiacal light and observations of calibration stars to correct for the fact that the large-scale sensitivity pattern varies with spectral shape. Using the “photometric correction” images from the Spitzer Science Center, we constructed correction mosaics and applied them to the M31 mosaics. We tested two different corrections for alternately red and blue sources and found that the effect was small. The magnitude changes for the red source correction are \((0.02, 0.0, 0.0, 0.0)\) in the sense that point sources become fainter and the scatter about this mean is \((0.16, 0.04, 0.02, 0.02)\). With the blue source correction stellar magnitudes in Table 1 become alternately red and blue sources and found that the effect was small. The magnitude changes for the red source correction are \((0.20, 0.13, 0.13, 0.10)\). Therefore, we have not implemented a correction of this type, as the effect is small, and the conclusions below are unaffected.

3. MIPS SURVEY

The MIPS resolution ranges from 6\(\prime\) at 24 \(\mu\)m to 40\(\prime\) at 160 \(\mu\)m. Gordon et al. (2006) described the MIPS program surveying M31, fit a stellar population plus dust grain model to the spectral energy distribution, and discussed the structure of M31 in terms of its interactions with M32 and NGC 205. Point sources were extracted from the seven individual MIPS 24 \(\mu\)m AOR mosaics that together cover approximately 1\(\arcmin\) \(\times\) 3\(\arcmin\) centered on M31.

The point-source extraction was done using the PSF-fitting program StarFinder (Diolaiuti et al. 2000) using a MIPS 24 \(\mu\)m model PSF appropriate for stars (Engelbracht et al. 2007). This method of extracting point-source photometry has been extensively tested on LMC Spitzer observations (Meixner et al. 2006) and found to produce high-quality point-source catalogs at 24 \(\mu\)m.

4. STELLAR PHOTOMETRY

Point-spread functions (PSFs) were taken from the MOPEX\(^3\) analysis release by the Spitzer Science Center. Sixteen realizations of the PSF differing in pixel phase were constructed for each of the IRAC channels at the survey pixel scale and combined with DAOPHOT (Stetson 1987). Two passes were made with the ALLSTAR PSF-fitting software for each of the four channels, yielding over a quarter of a million point sources at 3.6 \(\mu\m\) with a detection threshold of 2.5 \(\sigma\). At 8.0 \(\mu\m\) we detected 160,000 sources with the same threshold. Source lists were merged with the DAOMASTER program (Stetson 1993), using a 1 pixel matching radius. Calibrated following Reach et al. (2005) and using aperture corrections based on the PSFs, Figure 1 is the IRAC two-color diagram for these objects. It resembles the equivalent diagram for the LMC (Meixner et al. 2006). Dusty evolved

---

\(^i\) See http://ssc.spitzer.caltech.edu/irac/sat.html.
\(^2\) See http://ssc.spitzer.caltech.edu/irac/sens.html.

---

**TABLE 1**

Phottometry of the Infrared Brightest Stars

| Number | R.A. (J2000.0) | Decl. (J2000.0) | [3.6] | [4.5] | [5.8] | [8] |
|--------|----------------|----------------|-------|-------|-------|-----|
| J003648.82+395625.7....... | 9.20341 | 39.94046 | 10.87 7 | 10.82 5 | 10.80 2 | 10.71 3 |
| J003659.17+400336.6....... | 9.24653 | 40.06018 | 9.67 11 | 9.36 2 | 9.23 10 | 9.00 1 |
| J003700.47+395031.8....... | 9.25196 | 39.84217 | 10.26 5 | 10.07 3 | 10.02 5 | 9.88 2 |
| J003700.75+401914.0....... | 9.25311 | 40.32055 | 9.99 12 | 9.76 5 | 9.66 5 | 9.60 2 |
| J003700.97+395619.2....... | 9.25404 | 39.93867 | 10.18 18 | 10.79 21 | 12.12 40 | 11.19 30 |
| J003708.35+403034.8....... | 9.28479 | 40.59066 | 10.16 7 | 9.24 11 | 8.52 1 | 8.37 1 |
| J003708.38+403032.4....... | 9.28490 | 40.59091 | 10.33 7 | ... | 11.03 11 | 11.24 10 |
| J003708.54+394701.7....... | 9.28557 | 39.78380 | 10.82 7 | 10.92 5 | 10.93 7 | 10.79 5 |
| J003709.07+401450.0....... | 9.28779 | 40.24722 | 10.07 10 | 9.93 5 | 9.87 3 | 9.77 1 |
| J003709.53+403350.1....... | 9.28970 | 40.56933 | 10.98 5 | 10.81 7 | 10.91 2 | 10.87 7 |
| J003716.53+395705.7....... | 9.31886 | 39.95158 | 9.78 7 | 9.58 5 | 9.61 1 | 9.43 1 |

Notes.—Magnitudes are given together with an uncertainty in hundredths of a magnitude. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

---

**Fig. 1.**—IRAC two-color diagram for sources in M31. The magnitudes are standard IRAC Vega magnitudes.
stars are offset from the origin in Figure 1. Objects with $[5.8] - [8] > 1$ are young stellar objects and show some concentration to the ring of star formation in M31 (Habing et al. 1984), as seen in Figure 2. Figure 3 compares the luminosity functions in the inner and outer parts of the galaxy.

An estimate of the foreground star and background galaxy contamination may be obtained by comparison with a survey such as SWIRE (Lonsdale et al. 2004). Its lowest Galactic latitude field is ELAIS-N2; $b = +42^\circ$, compared to M31’s $b = -21.2^\circ$. Its IRAC two-color diagram is reproduced in Figure 4. The IRAC catalog in this field covers $\sim 4.2$ deg$^2$. To a magnitude limit of $[3.6] = 17$, there are 40,953 objects in the ELAIS-N2 catalog; scaled to the IRAC M31 area (3.08 deg$^2$), this corresponds to 29,895 objects, a tenth of the total to 17th magnitude in M31. The color distribution of the SWIRE sources extends farther to the red in $[5.8] - [8.0]$ than the IRAC M31 sources, but the M31 sources’ color extends farther to the red in $[3.6] - [4.5]$. The brighter M31 sources also extend farther to the red in $[3.6] - [8.0]$. All of these properties of the color distributions are consistent with the M31 sources being dominated by stellar objects rather than galaxies, particularly at the faint end.

Figure 5 is a color-magnitude diagram (CMD) depicting massive star evolution in M31. Most of the stars fall on a strong vertical feature. These are main-sequence and supergiant stars, together with significant contamination from foreground stars. The
horizontal feature at \([3.6] = 10\) mag shows the growth of circumstellar envelopes radiating at 300–1000 K. To enable follow-up of these objects, magnitudes for \([3.6] < 11\) mag are recorded in Table 1. M31 is only a 29% overdensity for \(9 < K < 11\) mag in the 2MASS point-source catalog. We therefore expect 1/1.29, i.e., 77% ± 6%, of the entries in Table 1 to be foreground. Figure 6 shows the SWIRE control field. Scaling the 268 ELAIS-N2 catalog with \([3.6] < 11\) mag to the area of our M31 field, we expect 196 such objects. There are 426 stars in the M31 field with \([3.6] < 11\) and measured \([8.0]\) mag. If we assume that foreground objects scale as cosec(b), the estimate of 196 foreground stars becomes 362, which provides an independent estimate of the percentage foreground contamination of 85% ± 7%. That is a 2σ detection of evolved stars in M31 with \([3.6] < 11\) mag.

The maximum luminosity \([3.6] = 9.5\) mag corresponds to \(M_{bol} \approx -11.9\) according to the supergiant bolometric corrections of Johnson (1966) for a distance of \(m - M = 24.4\) mag (Huterer et al. 1995). This is a conservative estimate, as \([3.6] = 9.5\) mag exceeds the saturation limits noted in § 2. Such high luminosities \([1–2.5 \times 10^6 L_{\odot}]\) are reached in the evolution of 120 \(M_{\odot}\) stars (Chiosi & Maeder 1986).

The tip of the asymptotic giant branch (AGB; Wood et al. 1983) at M31 lies at \([3.6] > 14\) mag: all the evolved stars shown in Figure 5 are supergiants. The positions of \(\eta\) Car and VY CMa are represented on the diagram, moved to the distance of M31. Data for these objects are from Smith et al. (2001), Polomski et al. (1999), and Whitelock et al. (1994). Most of the stars with \([3.6] \approx 10\) are bluer than these objects; they are presumably in an earlier evolutionary phase of thickening circumstellar envelopes.4 Figure 7 extends deeper into the CMD for M31. Although photometric errors become significant for \([3.6] \approx 17\), we see a large number of AGB stars, stretching from the tip at 14.4 to the detection limit at 17 mag. Figure 8 is the corresponding SWIRE control field.

---

4 RY Scuti is another case in point (Gehrz et al. 2001). It has \([3.8] - [8.9] \approx 2.9\) mag, but is considerably fainter than \(\eta\) Car and VY CMa at 3.6 µm.
We carried out completeness tests by adding artificial stars to the [3.6] image. Completeness falls to 50% at $\frac{1}{2} \frac{3}{6} \frac{15}{5}$ mag and drops to almost zero at 16.5 mag. We cross-correlated our catalog with that of Massey et al. (2006). Over 87,000 matches were found within 1.6, but only a handful of these have been spectroscopically classified. Indeed, only 11 of these matches are included in Table 1, and these are 21st and 22nd $V$ magnitude stars. Luminous blue variables are also known in M31 (Szeifert et al. 1996), but these have $K$ magnitudes between 13.9 and 17.6. Clearly, there are many stars representing the latest stages of evolution in the stellar population of M31 that are most prominent in the infrared.

We can also compare the CMD of M31 with that of M33 in Figure 9. McQuinn et al. (2007) plot the IRAC [3.6]–[8] color distribution by [3.6] mag in their Figure 19. In M33 $M_{3.6} < -10$ consists of AGB stars without dust; the other two histograms are carbon stars with dust. We consider the carbon star frequency of M31 in the next section.

5. SPECTRAL ENERGY DISTRIBUTIONS

We cross-correlated our source catalog with the 2MASS Sky Survey (Skrutskie et al. 2006) using the OpenSkyQuery facility.

---

Fig. 9.—Color distribution as a function of magnitude for comparison with M33; see McQuinn et al. (2007). In M33 major peaks in the histograms indicate AGB stars without dust ([3.6]–[8] ≤ 0), carbon stars with dust (0.5 ≤ [3.6]–[8] ≤ 2.5) and $M_{3.6} < -9$, and young stellar objects ([3.6]–[8] ≥ 4).

Fig. 10.—CMD for the matches with 6 < 2MASS.

Fig. 11.—CMD following the classification by Blum et al. (2006) of stars into supergiants (light gray), AGB oxygen-rich (black), and AGB carbon-rich (dark gray). [See the electronic edition of the Journal for a color version of this figure.]

We carried out completeness tests by adding artificial stars to the [3.6] image. Completeness falls to 50% at [3.6] = 15.5 mag and drops to almost zero at 16.5 mag. We cross-correlated our catalog with that of Massey et al. (2006). Over 87,000 matches were found within 1.6, but only a handful of these have been spectroscopically classified. Indeed, only 11 of these matches are included in Table 1, and these are (with two exceptions) 21st and 22nd $V$ magnitude stars. Luminous blue variables are also known in M31 (Szeifert et al. 1996), but these have $K$ magnitudes between 13.9 and 17.6. Clearly, there are many stars representing the latest stages of evolution in the stellar population of M31 that are most prominent in the infrared.

We can also compare the CMD of M31 with that of M33 in Figure 9. McQuinn et al. (2007) plot the IRAC [3.6]–[8] color distribution by [3.6] mag in their Figure 19. In M33 $M_{3.6} < -10$ consists of AGB stars without dust; the other two histograms are carbon stars with dust. We consider the carbon star frequency of M31 in the next section.

5. SPECTRAL ENERGY DISTRIBUTIONS

We cross-correlated our source catalog with the 2MASS Sky Survey (Skrutskie et al. 2006) using the OpenSkyQuery facility.
Fig. 12.—Spectral energy distributions for sources in 2MASS with mid-infrared excesses. The light and dark gray numbers refer to Table 2. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 12—Continued
Fig. 12—Continued
TABLE 2
2MASS 6× MATCHES

| Number | R.A. (J2000.0) | Decl. (J2000.0) | J       | H       | K       | [3.6]   | [4.5]   | [5.8]   | [8.0]   |
|--------|----------------|----------------|---------|---------|---------|---------|---------|---------|---------|
| 52     | 9.62906        | 40.30904       | 17.17   | 16.64   | 17.16   | 11.50   | 11.59   | 11.38   | 11.35   |
| 24     | 9.67014        | 40.47509       | 17.57   | 16.80   | 16.16   | 13.04   | 12.98   | 12.95   | 12.85   |
| 3      | 9.72386        | 40.49491       | 18.25   | 16.67   | 16.22   | 14.01   | 13.28   | 12.79   | 12.28   |
| 43     | 9.72643        | 40.62497       | 17.69   | 16.62   | 16.30   | 12.03   | 12.10   | 11.74   | 12.17   |
| 49     | 10.07809       | 40.60300       | 17.69   | 16.36   | 16.26   | 13.72   | 12.52   | 11.37   | 10.41   |
| 15     | 10.08307       | 40.56743       | 17.65   | 16.57   | 16.43   | 14.69   | 13.47   | 12.73   | 11.82   |
| 6      | 10.08431       | 40.67662       | 17.23   | 16.34   | 15.86   | 14.87   | 13.70   | 12.43   | 11.57   |
| 44     | 10.12849       | 40.70961       | 16.99   | 15.78   | 15.59   | 14.84   | 14.19   | 12.03   | 10.87   |
| 3075   | 10.13519       | 40.65016       | 16.37   | 15.20   | 15.22   | 15.18   | 14.90   | 11.97   | 10.16   |
| 2968   | 10.29796       | 41.13960       | 18.31   | 16.71   | 16.26   | 14.88   | 14.34   | 13.41   | 12.57   |
| 2947   | 10.33984       | 40.83079       | 17.83   | 16.77   | 16.26   | 14.45   | 14.04   | 11.49   | 9.66    |

Note.—Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
of the National Virtual Observatory. Some 923 matches were found. To go deeper in the near-infrared, we downloaded a catalog from the ancillary data products of the 2MASS Extended Mission. This derives from a set of special observations made at the end of 2MASS survey operations that used exposure times 6 times longer than the main survey. These measurements reach 1 mag deeper than the survey. We found 3110 matches with the 6× catalog within a 1.6° radius.

Figure 10 is a CMD plotted from these matches. Following the deep JHK photometry of M33 by Cioni et al. (2008) the strong vertical feature with \( J - K < 1 \) and \( K < 14.5 \) is foreground, mixed with M supergiants. The broader vertical feature with \( K > 14.5 \) are M-type AGB stars, and stars with \( J - K > 1.36° \) are candidate carbon stars. The principal difference between M31 and M33, besides the fact that the UKIRT M33 photometry goes deeper, is that the branch of carbon stars at \( K = 16 \) mag (in Fig. 2 of Cioni et al. 2008) is mostly absent, replaced by a dozen or so stars in M31 at \( K \approx 14 \) mag. The product of third dredge-up, carbon stars are harder to make in metal-rich envelopes (Renzini & Voli 1981).

Blum et al. (2006) have classified stars in the SAGE survey of the LMC (Meixner et al. 2006) according to their position in the [3.6], \( J - [3.6] \) CMD. Figure 11 reproduces this classification for an LMC distance modulus of 18.5 (Mould et al. 2000). Supergiants are separated in color from AGB M stars, which are in turn separated from AGB C stars. In the LMC this separation is clearly made into distinct concentrations in the Hess diagram, in which the RGB tip, the oxygen-rich, and carbon-rich AGB branches are clearly visible. In M31 the IRAC/2MASS CMD is sparser and noisier, and additional dredge-up may be required to overcome additional metallicity and make carbon stars. Classification based on Figure 10 may be indicative rather than exact, until spectroscopy can be obtained at 14 < [3.6] < 16 and \( J - K \approx 2 \).

Matching with 6× 2MASS allowed spectral energy distributions (SEDs) to be plotted from 1 to 8 \( \mu m \). Foreground stars will tend to show photospheric SEDs. For those stars showing a mid-infrared excess (defined as a peak at 3.6 \( \mu m \) or beyond), we display SEDs in Figure 12 and magnitudes in Table 2. Three broad classes of sources are seen in Figure 12: (1) those that peak at 3.6 \( \mu m \), (2) sources with a longer wavelength excess, and (3) relatively flat spectrum sources. The first class are consistent with rather warm circumstellar envelopes (\( \sim 1000 \) K); in class (2) the envelope is cooler (\( \leq 500 \) K); class (3) would be consistent with compact H \( \alpha \) regions, supernovae remnants, or planetary nebulae, especially if the approximately flat spectrum extends to 24 \( \mu m \) (Verley et al. 2007). Omitted from Figure 12 are cases where DAOMASTER failed to match a star at an individual wavelength. There are approximately 20 such cases for which spurious peaks appear in the SED.

Bolometric corrections are not tabulated for stars as red as some of these objects. Integrating these SEDs from 1 to 10 \( \mu m \), we obtain luminosities from 1 to \( 20 \times 10^4 \) \( L_\odot \) for those that are members of M31. The majority of these stars are AGB stars with circumstellar envelopes; there are 12 that are nominally supergiants.

### Table 3

| MSH (2004) No. | \( J \) | \( H \) | \( K \) | [3.6] | [4.5] | [5.8] | [8] |
|----------------|-------|-------|-------|-------|-------|-------|-----|
| 11009          | 18.05 | 16.84 | 16.38 | 16.03 | 15.93 |
| 12008          | 17.12 | 16.07 | 16.03 | 16.23 |
| 12022          | 17.63 | 17.40 | 16.17 |
| 12026          |       | 17.42 | 16.45 |
| 12034          |       | 17.30 | 17.20 | 16.68 |
| 12040          | 17.90 | 17.03 | 16.74 | 15.84 | 15.60 |
| 12041          | 18.43 | 17.08 | 17.54 | 15.80 | 15.98 |
| 12042          | 17.59 | 17.03 | 17.47 | 16.00 | 14.99 | 14.36 | 13.10 |
| 12052          |       | 17.97 |       | 16.30 |
| 12080          | 18.58 |       | 16.19 |
| 12090          | 18.02 | 17.43 | 17.82 | 15.42 |
| 12092          |       | 17.82 | 17.80 | 16.59 |
| 13002          | 18.53 | 17.76 | 17.16 | 16.04 | 16.21 |
| 13012          | 17.98 | 17.50 | 16.98 | 15.42 | 15.29 | 14.59 |
| 13013          | 17.90 | 17.26 | 16.95 | 15.70 | 16.11 |
| 13021          | 16.15 | 15.92 | 14.90 | 16.52 |

**Note:** Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

---

**Fig. 14.—CMD for M31’s LPVs.**
(\(M_{\text{bol}} < -7\)), mostly with warm circumstellar envelopes. We cannot rule out that some of these stars may be late-type dwarfs in the foreground.

6. LONG-PERIOD VARIABLES

The catalog was also cross-correlated with the long-period variable (LPV) catalog of Mould et al. (2004), which covers about half of the disk of M31. We found 831 sources within 2.5\(\degree\)00 of LPVs, triple the number that would have been expected by chance. The matches appear in Table 3 and comprise over 40\% of the LPV catalog. Figure 13 is the IRAC two-color diagram for LPVs, and Figure 14 is a CMD.

The distribution of points in Figure 14 is bounded by the limits of Mould et al.’s (2004) photometry at \(J \approx 18.5\) and the present photometry [3.6] \(\approx 17\) mag. With \(\langle K \rangle = 16.38\) mag, these LPVs have \(M_{\text{bol}} \approx -5\) and are AGB stars. This contrasts with the LMC and M33, which show significant numbers of supergiant LPVs with \(M_{\text{bol}} < -7\) in addition to their AGB population (Wood et al. 1983; Mould et al. 1990).

7. MIPS SOURCES

Over 25,000 sources from 1 to 0.2 mJy were extracted from the MIPS 24 \(\mu\)m image. Sources that are bright at 24 \(\mu\)m include H\(\alpha\) regions, supernova remnants, and planetary nebulae (Verley et al. 2007). Nevertheless, cross-correlation with the brightest six magnitudes of the IRAC stellar catalog yielded 599 matches within 1.00, and these are found in Table 4. Sixty matches would have been expected by chance. Figure 15 shows that many of these matches fall on the dusty stars side of the IRAC-MIPS two-color diagram, rather than the young stellar objects side (Meixner et al. 2006). J004258.15+410731.3 is 667 day period LPV 33133. J004031.89+410624.7 is 785 day period LPV 14023. These are three of the 20 longest periods in the LPV catalog. Their SEDs are shown in Figure 16. These extreme period LPVs appear to show two components: a photospheric component, and

| SSTM1M311 No.          | R.A. (J2000.0) | Decl. (J2000.0) | [3.6] | [4.5] | [5.8] | [8]  | [24] |
|------------------------|----------------|----------------|-------|-------|-------|------|------|
| J003921.35+402142.2     | 9.83898        | 40.36174       | 13.98 | 13.84 | 13.67 | 13.65| 9.50 |
| J004004.56+403844.1     | 10.01900       | 40.64558       | 14.62 | 14.55 | 13.98 | 13.51| 10.42|
| J004014.35+404836.3     | 10.05983       | 40.81009       | 15.12 | 14.55 | 13.83 | 13.46| 10.59|
| J004031.52+404126.6     | 10.13134       | 40.69073       | 15.86 | 15.49 | 12.64 | 10.75| 5.63 |
| J004032.94+403901.7     | 10.13728       | 40.65049       | 14.89 | 14.82 | 12.36 | 10.65| 8.32 |
| J004034.74+403426.6     | 10.18226       | 40.72406       | 15.51 | 15.20 | 14.35 | 12.88| 10.70|
| J004046.28+403234.6     | 10.19284       | 40.55685       | 16.04 | 15.03 | 14.19 | 12.96| 9.93 |
| J004054.09+404606.5     | 10.22541       | 40.76847       | 15.68 | 15.58 | 14.39 | 12.43| 10.11|
| J004055.89+404644.3     | 10.23291       | 40.77898       | 16.03 | 15.36 | 12.57 | 9.16 |
| J004057.04+404935.8     | 10.23771       | 40.82663       | 15.75 | 15.22 | 14.30 | 13.92| 9.65 |
| J004059.78+403530.7     | 10.24912       | 40.59188       | 11.39 | 11.35 | 11.14 | 10.87| 10.35|
| J004102.24+410432.1     | 10.25936       | 41.07561       | 15.73 | 15.51 | 12.80 | 10.77| 8.31 |
| J004104.65+405428.4     | 10.26940       | 40.90791       | 12.43 | 12.53 | 12.28 | 12.25| 11.34|

Note.—Table 4 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

![Fig. 15.—IRAC-MIPS two-color diagram for bright sources in M31 from Table 4. According to Meixner et al. (2006), young stellar objects lie on the right side of the dashed line.](image)

![Fig. 16.—Spectral energy distributions for three LPVs. The light and dark gray numbers are those of Mould et al. (2004). [See the electronic edition of the Journal for a color version of this figure.]](image)
a dust shell that is relatively cool compared with those illustrated in § 5.

The luminosity function of 24 μm sources is illustrated in Figure 18. Brighter sources tend to be contained within M31’s ring of star formation and are more likely to be compact H II regions or young stellar objects.

8. CONCLUSIONS

Our Spitzer Space Telescope survey reveals a rich population of evolved stars in M31. Although there is strong foreground contamination, supergiants are present as bright as (1 – 2.5) × 10^6 L☉. These evolve into stars with extensive circumstellar envelopes like η Carinae and VY CMa in the Milky Way. A number of the brightest supergiants at 3.6 μm are so red that they will be missed in optical surveys. We also resolve stars below the tip of the AGB to Mbol = −5 mag. Many of these are LPVs, which also have dusty envelopes. Photometric candidates for AGB carbon stars are much fewer in M31 than M33, but spectroscopy is required to quantify this.

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 a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech. This work makes use of 2MASS data products, a joint project of the University of Massachusetts and IPAC/Caltech, funded by NASA and NSF. In addition to DAOPHOT, this research has made use of IRAF, which is distributed by NOAO. NOAO is operated by AURA under a cooperative agreement with NSF.

REFERENCES

Baade, W. 1944, ApJ, 100, 137
Baade, W., & Swope, H. 1963, AJ, 68, 435
Barmby, P., et al. 2006, ApJ, 650, L45
Berkhuijsen, E., Humphreys, R., Ghigo, F., & Zunach, W. 1988, A&AS, 76, 65
Blum, R., et al. 2006, AJ, 132, 2034
Cannon, J., et al. 2006, ApJ, 652, L45
Chiosi, C., & Maeder, A. 1986, ARA&A, 24, 329
Cioni, M.-R. L., et al. 2008, A&A, 487, 131
Diolaiti, E., Bendinelli, O., Bonacini, D., Close, L., Currie, D., & Parmeggiani, G. 2000, A&AS, 147, 335
Engelbracht, C. W., et al. 2007, PASP, 119, 994
Fazio, G. G., et al. 2004, ApJS, 154, 10
Gehrz, R. D., et al. 2001, ApJ, 559, 395
———. 2007, Rev. Sci. Instrum., 78, 011102
Gordon, K., et al. 2006, ApJ, 638, L87
Habing, H., et al. 1984, ApJ, 278, L59
Herrero, A., et al. 1994, A&A, 287, 885
Hodge, P. 1981, Atlas of the Andromeda Galaxy (Seattle: Univ. Washington Press)
Hubble, E. 1936, The Realm of the Nebulae (New Haven: Yale Univ. Press)
Hubble, E., & Sandage, A. 1953, ApJ, 118, 353
Humphreys, R. 1979, ApJ, 234, 854
Humphreys, R., Massey, P., & Freedman, W. 1990, AJ, 99, 84
Humphreys, R., et al. 1988, AJ, 96, 1884
———. 2006, AJ, 131, 2105
Huterer, D., Sasselov, D., & Schechter, P. 1995, AJ, 110, 2705
Jackson, D., et al. 2006, ApJ, 646, 192
———. 2007a, ApJ, 656, 818
———. 2007b, ApJ, 667, 891
Jarrett, T., et al. 2003, AJ, 125, 525
Johnson, H. 1966, ARA&A, 4, 193
Kraemer, K., et al. 2002, AJ, 124, 2990
Lee, M. G., et al. 2002, ApJ, 565, 959
Lonsdale, C., et al. 2004, ApJS, 154, 54
Magnier, E., et al. 1992, A&AS, 96, 379
Massey, P. 1998, ApJ, 501, 153
Massey, P., et al. 2006, AJ, 131, 2478
McQuinn, K., et al. 2007, ApJ, 664, 850
Meixner, M., et al. 2006, AJ, 132, 2268
Mohrĳeška, B., Kuznecnov, K., & Sasselov, D. 2001, AJ, 122, 1383
Mould, J., & Kristian, J. 1986, ApJ, 305, 591
Mould, J., Saha, A., & Hughes, S. 2004, ApJS, 154, 623
Mould, J., et al. 1990, ApJ, 349, 503
———. 2000, ApJ, 529, 786
Odenwald, S., Newmark, J., & Smoot, G. 1998, ApJ, 500, 554
Olsen, K., et al. 2006, AJ, 132, 271
Polomski, E., et al. 1999, AJ, 118, 2369
Reach, W., et al. 2005, PASP, 117, 978
Renzini, A., & Voli, M. 1981, A&A, 94, 175
Rieke, G. H., et al. 2004, ApJS, 154, 25
Rieke, G. H., et al. 2004, ApJS, 154, 175
Schlegel, D., Finkbeiner, D., & Davis, M. 1998, ApJ, 500, 525
Skrutskie, M., et al. 2006, AJ, 131, 1163
Smith, N., et al. 2001, AJ, 121, 1111
Stetson, P. 1987, PASP, 99, 191
———. 1993, in IAU Colloq. 136, Stellar Photometry—Current Techniques and Future Developments, ed. C. J. Butler & I. Elliot (Cambridge: Cambridge Univ. Press), 291
Szeifert, T., et al. 1996, A&A, 314, 131
Verley, S., et al. 2007, A&A, 476, 1161
Werner, M. W., et al. 2004, ApJS, 154, 1
White, P. R., Bessell, M. S., & Fox, M. W. 1983, ApJ, 272, 99
Xu, C., & Helou, G. 1996, ApJ, 456, 152

Fig. 17.—Spectral energy distributions for five bright 24 μm sources in M31. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 18.—Luminosity function for 24 μm sources. The dashed histogram is for sources contained within M31’s ring of star formation. [See the electronic edition of the Journal for a color version of this figure.]