MID-INFRARED PHOTOMETRY OF MASS-LOSING ASYMPTOTIC GIANT BRANCH STARS

M. BUSSO AND R. GUANDALINI
Department of Physics, University of Perugia, Perugia 06123, Italy; busson@fisica.unipg.it, guandalini@fisica.unipg.it

P. PERSI
INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica, 00100 Roma, Italy; persi@iasf-vm.inaf.it

L. CORCIONE
INAF, Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy; corcione@oa-torino.inaf.it

AND

M. FERRARI-TONIOLO
INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica, 00100 Roma, Italy; ferrari@iasf-vm.inaf.it

Received 2006 September 28; accepted 2007 January 5

ABSTRACT

We present ground-based mid-IR imaging for 27 M-, S-, and C-type asymptotic giant branch (AGB) stars. The data are compared with those of the database available thanks to the IRAS, Infrared Space Observatory, Midcourse Space Experiment, and Two Micron All Sky Survey catalogs. Our goal is to establish relations between the IR colors, the effective temperature Teff, the luminosity L, and the mass-loss rate Ṁ, for improving the effectiveness of AGB modeling. Bolometric (absolute) magnitudes are obtained through distance compilations and by applying previously derived bolometric corrections; the variability is also studied, using data accumulated since the IRAS epoch. The main results are as follows: (1) Values of L and Ṁ for C stars fit relations previously established by us, with Mira variables being on average more evolved and mass-losing than semiregular variables. (2) Moderate IR excesses (as compared to evolutionary tracks) are found for S and M stars in our sample; they are confirmed to originate from the dusty circumstellar environment. (3) A larger reddening characterizes C-rich Mira variables and post-AGB stars. In this case, part of the excess is due to AGB models overestimating Teff for C stars, as a consequence of the lack of suitable molecular opacities. This has a large effect on the colors of C-rich sources, and sometimes disentangling the photospheric and circumstellar contributions is difficult; better model atmospheres should be used in stellar evolutionary codes for C stars. (4) The presence of a long-term variability at mid-IR wavelengths seems to be limited to sources with maximum emission in the 8–20 μm region, usually Mira variables (one-third of our sample). Most of the semiregular and post-AGB stars studied here have remained remarkably constant in the mid-IR over the last 20 years.

Key words: infrared: stars — stars: AGB and post-AGB — stars: carbon — stars: mass loss

1. INTRODUCTION

Stars of low and intermediate mass (all those below M = 7–8 M☉) terminate their evolution through the so-called asymptotic giant branch (AGB) phase (Busso et al. 1999; Busso 2007), in which they lose mass efficiently thanks to stellar winds powered by radiation pressure on dust grains (Habing 1996). After this stage, they generate planetary nebulae and start a blueward path, which ultimately gives birth to a white dwarf (see also Herwig 2005).

While moving along this path, AGB stars replenish the interstellar medium with about 70% of all the matter returned after stellar evolution (Sedlmayr 1994); this is done through the formation of extended circumstellar envelopes (Winters et al. 2002). Cool or cold dust, with its radiative emission in the IR, normally dominates the energy distribution of these sources, so that until recently the bolometric (apparent) magnitude of the most evolved AGB stars was difficult to derive due to insufficient photometric coverage of the mid- to far-IR range of the electromagnetic spectrum. Traditionally, circumstellar envelopes have been studied using fluxes provided by IRAS (see Jura 1986; Jura & Kleinmann 1989), which had, however, a poor spatial resolution (and hence some risk of contamination, especially at the longest wavelengths).

Similarly, absolute magnitudes were very uncertain due to the difficulties in measuring the distance of these single, strongly variable stars.

Only recently has the availability of a large IR database from space-borne telescopes such as the Infrared Space Observatory (ISO), Infrared Telescope in Space, and Midcourse Space Experiment (MSX) and the increased amount of ground-based mid-IR observations substantially modified the situation. The quantitative studies of luminosities, colors, and mass loss in the last evolutionary stages of moderately massive stars have consequently grown in number and quality (Whitelock et al. 2006; Feast et al. 2006). In parallel, Hipparcos distances for AGB stars have been in part upgraded (Bergeat & Chevallier 2005). The results may still include inconsistencies (M. W. Feast 2006, private communication), but a full revision of the Hipparcos catalog is still expected (van Leeuwen 2005; van Leeuwen & Fantino 2005). Recent works have therefore largely exploited period-luminosity relations to infer the distances (Menzies et al. 2006; Feast 2007). Contemporarily, the first results of the Spitzer Space Telescope’s surveys are becoming available (Zijlstra et al. 2006).

In the above modified scenario we started a reanalysis of Galactic AGB stars at IR wavelengths, aimed at improving the determination of their energy distribution, mass losses, and absolute magnitudes, making use of recent IR photometric data and of reliable distance estimates. With such works one can now finally compare homogeneous samples of mass-losing stars in the Galaxy with similar data sets in the Magellanic Clouds (van Loon et al. 2001, 2005) in order to study the dependence on metallicity of general stellar properties.
In a previous paper (Guandalini et al. 2006, hereafter Paper I) we considered C stars as observed by the ISO SWS and MSX. Here we extend our work by analyzing a sample of 27 AGB stars of classes M, S, and C (listed in Table 1) for which we obtained ground-based IR imaging in the 10 μm window. Most of the stars we observed were also the object of measurements by the above quoted space-borne IR telescopes, so that we can now compare and integrate results from different experiments and different epochs as a check of the quality of the available IR database and of the source variability.

This paper is organized as follows: in § 2 we briefly discuss the IR camera used for making the ground-based observations. In § 3 we present the photometric data obtained through it at wavelengths longer than 8 μm, integrated by the near-IR archive observations of the Two Micron All Sky Survey (2MASS)\(^1\) and by the available estimates for mass-loss rates, distances, and a few other relevant parameters. In § 4 we then use the database thus constructed to derive bolometric magnitudes (both apparent and absolute), colors, and correlations of photometric properties with mass-loss rates. Then § 5 addresses the long-term variability issue by going back to the IRAS catalogs in order to compare the available data over a time interval of about 20 years. Finally, in § 6 we outline some general conclusions, underlining the main problems that remain to be solved to allow a satisfactory match between photometric observations and stellar modeling.

### 2. THE MID-IR CAMERA TIRCAM2 AND ITS CALIBRATION

Our sample stars were observed between 2001 and 2004 at the Italian infrared telescope TIRGO, located 3200 m above sea level, on top of the Gornergrat in Switzerland. The data were collected using our mid-IR camera TIRCAM2 (TIRGO Infrared Camera, ver. 2), an upgrade of a previously available instrument (Persi et al. 1994).

TIRCAM2 uses a Rockwell (now Boeing) high-flux Si:As BIB 128 × 128 array (HF-21) and is equipped with five narrow-band filters (10% bandwidth) between 8 and 13 μm, with the N broadband filter and a circular variable filter having a spectral resolution of 3% in the 8–14 μm range. The optics of the camera produce a plate scale at TIRGO of 0.77" pixel\(^{-1}\). The array, the optical system, and the filters are assembled in a liquid-He-cooled dewar (HD-3[8]) from Infrared Labs, Inc. (Tucson, Arizona). The readout electronics of the array, fully developed by our home institute, and the other general characteristics of the instrument have been previously described elsewhere (Persi et al. 2002; Corcione et al. 2003). The absolute fluxes of some IR standard stars in our photometric system are shown in Table 2. They have been derived from the spectral energy distributions (SEDs) published by Cohen and coworkers (Cohen et al. 1999 and references 1 VizieR Online Data Catalog, II/246 (R. M. Cutri et al., 2003).

### TABLE 1
The TIRCAM2 Sample of AGB Stars

| Number | IRAS Name | Other Name | R.A. (J2000.0) | Decl. (J2000.0) | Variability Type | Type |
|--------|-----------|------------|----------------|----------------|-----------------|------|
| 1      | 0114+6658 | RAFGL 190  | 01 17 51.62    | +67 13 55.4    | P               | C    |
| 2      | 0318+7016 | RAFGL 482  | 03 23 36.57    | +70 27 07.5    | M               | C    |
| 3      | 0430+6210 | IRC +60144 | 04 35 17.45    | +62 16 23.3    | S               | C    |
| 4      | 0439+3601 | RAFGL 618  | 04 42 53.67    | +36 06 53.2    | P               | C    |
| 5      | 0453+4427 | RAFGL 6319S| 04 56 43.28    | +44 32 41.6    | ...             | C    |
| 6      | 0540+3240 | RAFGL 809  | 05 43 49.78    | +32 42 06.8    | M               | C    |
| 7      | 0542+2040 | Y Tau      | 05 45 39.41    | +20 41 42.1    | S               | C    |
| 8      | 0601+0726 | RAFGL 865  | 06 03 59.84    | +07 25 54.4    | M               | C    |
| 9      | 0617+1036 | Red Rectangle | 06 19 58.22 | −10 38 14.7 | P               | C    |
| 10     | 0629+4319 | RAFGL 954  | 06 32 41.93    | +43 17 15.3    | I               | C    |
| 11     | 0713+1005 | HD 56126   | 07 16 10.26    | +09 59 48.0    | P               | C    |
| 12     | 0945+1330 | CW Leo     | 09 47 57.38    | +13 16 43.7    | M               | C    |
| 13     | 1013+3049 | CIT 6      | 10 16 02.27    | +30 34 18.6    | S               | C    |
| 14     | 1242+4542 | Y CVn      | 12 45 07.83    | +45 26 24.9    | S               | C    |
| 15     | 1247+0425 | RU Vir     | 12 47 18.41    | +04 08 41.4    | M               | C    |
| 16     | 1254+6615 | RY Dra     | 12 56 25.91    | +65 59 39.8    | S               | C    |
| 17     | 0633+1415 | DY Gem     | 06 35 57.81    | +14 12 46.1    | S               | S    |
| 18     | 0907+3110 | RS Cnc     | 09 10 38.80    | +30 57 47.3    | S               | S    |
| 19     | 1241+6121 | S UMa      | 12 43 36.68    | +61 05 35.5    | M               | S    |
| 20     | 1549+4837 | ST Her     | 15 50 46.62    | +48 28 58.9    | S               | S    |
| 21     | 0629+4045 | IRC +40156 | 06 33 15.75    | +40 42 50.9    | P               | M    |
| 22     | 1227+0441 | BK Vir     | 12 30 21.01    | +04 24 59.2    | S               | M    |
| 23     | 1300+0527 | RT Vir     | 13 02 37.98    | +05 11 08.4    | S               | M    |
| 24     | 1405+4405 | BY Boo     | 14 07 55.76    | +43 51 16.0    | I               | M    |
| 25     | 1421+2555 | RX Boo     | 14 24 11.63    | +25 42 13.4    | S               | M    |
| 26     | 1437+3245 | RV Boo     | 14 39 15.86    | +32 32 22.3    | S               | M    |
| 27     | 1626+4159 | g Her      | 16 28 35.51    | +41 52 54.0    | S               | M    |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Variability types: (M) Mira; (S) semiregular; (I) irregular; (P) post-AGB. Ellipses are for all stars of unknown variability.

### TABLE 2
Flux Densities of Standard Stars

| Standard | [8.8] (Jy) | [9.8] (Jy) | [11.7] (Jy) | [12.5] (Jy) |
|----------|------------|------------|-------------|-------------|
| α Lyr    | 49.69      | 40.44      | 28.48       | 25.05       |
| β Gem    | 152.74     | 120.90     | 88.67       | 76.77       |
| α Boo    | 883.72     | 745.32     | 524.94      | 459.01      |
| β And    | 306.36     | 263.52     | 200.79      | 174.55      |
| β Peg    | 431.12     | 376.00     | 279.25      | 249.01      |
| α Tau    | 752.09     | 646.86     | 481.44      | 419.57      |
therein) after a convolution with the spectral response of our filters
(Persi et al. 2002). The narrowband images at 8.8, 9.8, 11.7, and 12.5 μm of our sample of AGB stars were taken in the standard chopping and nodding technique in order to remove the sky and telescope emission background. Images of standard stars were obtained during the nights with an air mass similar to that of our targets for flux calibration. They were also used to estimate the point-spread function (PSF) at each wavelength. The mean PSF (FWHM) obtained during our observing runs was ~3.2" in diameter at 8.8 μm and ~3.8" at 12.5 μm. All the observed AGB stars appear as pointlike sources at this spatial resolution. The on-source integration times were from 720 s for the faintest sources, down to 120 s for the brightest ones, in all the filters used. The derived detection limit is approximately 0.7 Jy (1 σ) in 300 s of integration time. The photometric measurements were extracted from the images of the AGB stars through the DAOPHOT tool in the IRAF data reduction package (Stetson 1987), using an aperture of 6".

### 3. INFRARED COLORS AND MASS LOSS OF AGB SOURCES

The flux densities of the sources observed, as measured with the technique mentioned in § 2, are given in Table 3, together with their 1 σ statistical errors. We collected, as a comparison, near-IR fluxes for our sources as published in the 2MASS catalog, together with observations by the MSX satellite (when available) for wavelengths longer than those of our filters. These data are presented in Table 4. Finally, distances, mass-loss rates, and wind velocities as deduced by the literature are presented in Table 5, together with the relevant references.

By calibrating the data of Table 3 with the zero-magnitude fluxes deduced by standard stars in Table 2, we obtain the IR colors of the sources. Examples of color-color diagrams are shown in Figures 1 and 2. Here TIRCAM2 sources are represented by big symbols. Open starred symbols refer to M-type (oxygen-rich) stars, and open unstarrred symbols to S-type stars. Filled symbols indicate C-rich sources. Small circles refer to the sample of C stars we discussed in Paper I, with colors deduced from ISO and MSX observations, as a comparison (see Fig. 6 in Paper I). We recall that the ISO data were taken from the last online database available, in which SWS measurements are fully calibrated (Leech et al. 2004). From them we derived photometric estimates in the TIRCAM2 photometric system by convolving SWS spectra with the response curves of our filters (see Paper I).

The bulk of our data are generally distributed along the line of blackbody emission in Figure 1, while a larger dispersion is present in Figure 2. The spread in Figure 2 derives from the fact that, for sources that are presently on the AGB (semiregular or Mira variables), color indices computed in the 8–14 μm region are affected by the crowding of variable emission (or absorption) features characteristic of these wavelengths (e.g., at 11.2–11.7 μm for C stars, from polycyclic aromatic hydrocarbons and SiC; and at 9.8 μm for O-rich sources, from silicates). When colors outside the 8–14 μm band are used (Fig. 1), excess emission at 21 μm is seen for a number of post-AGB, C-rich TIRCAM2 sources (as also shown by ISO and MSX data; see Paper I). Emission at this wavelength was known to be a distinctive property of a few post-AGB C stars and C-rich protoplanetary nebulae (Kwok et al. 2002; Zhang et al. 2006). However, so far the number of known sources with this feature has been rather limited: in our data (both

---

**TABLE 3**

| Source Number | Epoch    | $F[8.8]$ (Jy) | $F[9.8]$ (Jy) | $F[11.7]$ (Jy) | $F[12.5]$ (Jy) |
|---------------|----------|--------------|--------------|--------------|--------------|
| 1             | 2003 Jan 16 | 73.5 ± 5.4  | 29.2 ± 8.2   | 78.9 ± 11.3  | 109.6 ± 14.4 |
| 2             | 2003 Jan 16 | 147.1 ± 7.9  | 156.5 ± 10.9 | 133.1 ± 16.4 | 145.4 ± 19.2 |
| 3             | 2003 Dec 6  | 254.6 ± 27.1 | 380.2 ± 42.8 | 490.2 ± 62.6 | 488.0 ± 28.4 |
| 5             | 2003 Feb 13 | 87.2 ± 19.1  | 83.0 ± 8.3   | 100.1 ± 10.0 | 87.8 ± 9.0   |
| 6             | 2006 Jan 16 | 185.6 ± 9.3  | 158.2 ± 11.9 | 143.1 ± 17.5 | 169.5 ± 21.5 |
| 7             | 2002 Feb 12 | 122.6 ± 13.5 | 116.8 ± 7.4  | 133.0 ± 6.7  | 80.9 ± 3.6   |
| 8             | 2003 Dec 6  | 364.9 ± 28.9 | 414.1 ± 41.1 | 477.9 ± 34.6 | 379.1 ± 43.2 |
| 9             | 2003 Dec 7  | 301.5 ± 34.2 | 307.5 ± 50.4 | 387.2 ± 35.9 | 387.4 ± 49.0 |
| 10            | 2004 Jan 15 | 63.4 ± 6.6   | 66.2 ± 14.6  | 129.1 ± 12.6 | 81.6 ± 24    |
| 11            | 2004 Jan 16 | 5.6 ± 1.8    | 10.7 ± 2.4   | 7.3 ± 2.8    | 20.6 ± 2.7   |
| 12            | 2001 Jan 14 | 30255 ± 605  | ...          | 41782 ± 342  | 38978 ± 667.9|
| 13            | 2003 Jan 15 | 1789 ± 156   | 1976 ± 190   | 2226 ± 400   | ...          |
| 14            | 2003 Dec 6  | 342.8 ± 20.3 | 337.0 ± 29.0 | 108.9 ± 22.0 | 220.7 ± 24.6 |
| 15            | 2003 Jan 16 | 233.0 ± 27.6 | 252.4 ± 24.3 | 245.7 ± 39.3 | 208.8 ± 25.5 |
| 16            | 2003 Jan 16 | 140.1 ± 15.7 | 83.0 ± 10.7  | 84.4 ± 13.8  | 104.4 ± 13.4 |
| 17            | 2004 Feb 6  | 5.3 ± 3.2    | 16.4 ± 11.4  | 34.7 ± 12.5  | 24.5 ± 4.5   |
| 18            | 2001 Jan 14 | 398.4 ± 40.0 | 550.0 ± 82.5 | 453.1 ± 63.4 | 378.3 ± 57.0 |
| 20            | 2002 Feb 11 | 568.5 ± 47.8 | 790.7 ± 29.8 | 497.2 ± 13.0 | 452.1 ± 33.0 |
| 21            | 2003 Dec 6  | 570.0 ± 30.0 | 739.1 ± 49.0 | 530.0 ± 37.0 | 477.1 ± 28.0 |
| 22            | 2002 Feb 11 | 4.5 ± 0.5    | ...          | 2.8 ± 0.5    | 3.1 ± 0.7    |
| 24            | 2004 Feb 4  | 155.7 ± 8.0  | 205.2 ± 33.0 | 201.4 ± 50.0 | 215.5 ± 28.0 |
| 33            | 2004 Jan 14 | 209.4 ± 10.8 | 334.1 ± 37.8 | 321.4 ± 69.0 | 134.9 ± 10.0 |
| 25            | 2004 Feb 4  | 224.6 ± 11.3 | 217.6 ± 32.6 | 118.4 ± 29.6 | 211.6 ± 27.5 |
| 26            | 2004 Feb 6  | 365.7 ± 16.4 | 496.4 ± 24.0 | 394.3 ± 22.4 | 432.5 ± 54.3 |
| 27            | 2002 Feb 12 | 777.7 ± 8.6  | 72.2 ± 1.3   | 516.2 ± 26.6 | 40.2 ± 2.3   |
| 28            | 2002 Feb 11 | 694.8 ± 58.4 | 922.2 ± 34.7 | 795.8 ± 20.5 | 729.2 ± 52.9 |
| 29            | 2004 Feb 6  | 106.7 ± 13.9 | 151.3 ± 47.2 | 75.1 ± 21.0  | 86.4 ± 8.6   |
| 30            | 2002 Feb 12 | 461.6 ± 50.9 | 427.4 ± 27.0 | 340.4 ± 17.3 | 293.6 ± 13.2 |
here and in Paper I) the 21 μm emission appears as a general property of post-AGB sources. The above simple considerations confirm the fact that mid-IR colors are effective tools for classifying AGB sources. When one deals with IR stars, mid-IR colors identify C-rich AGB stars through their color excess at 11.7 μm and C-rich post-AGB stars through their 21 μm excess.

Figure 3 then shows the relations linking the IR colors to mass loss. Again, the best measurements selected for C stars in Paper I are included for comparison. It is clear that our new C-star data follow the trends already established, as expected. However, it is also evident that the (few) O-rich sources of the sample behave differently, displaying lower mass-loss rates for a given value of the color, especially when this last makes use of fluxes in the 10 μm region (Fig. 3a). Should this hint be confirmed, this would mean that the relation between dust opacities and mass-loss rates for M and S stars has to be different from that for C stars. We are now verifying this in a dedicated work on a much larger database (R. Guandalini & M. Busso 2007, in preparation).

4. COLOR-MAGNITUDE DIAGRAMS AND EFFECTIVE TEMPERATURES

By applying to our database the bolometric corrections discussed in Paper I, we can easily derive the apparent bolometric magnitudes of the C-rich sources studied. For O-rich S and M stars we applied instead the bolometric correction (Guandalini et al. 2007)

\[ M_{\text{bol}} - M_{[8.8]} = ax^3 + bx^2 + cx + d, \]

where \( x \) is the \( K - [8.8] \) color and the coefficients are
\[ a = -0.0211, \quad b = 0.0812, \quad c = 1.0658, \quad \text{and} \quad d = 2.3026 \] (with a correlation \( r^2 = 0.989 \)). Correcting for the distance (see Table 5) yields the absolute bolometric magnitude, through which the absolute color-magnitude diagram can be plotted. Examples are presented in Figures 4 and 5.

In Figure 4 the hatched area represents the zone occupied by AGB photospheres according to current stellar models (Straniero et al. 1997). As the figure shows, essentially all the stars of our sample, much like those of Paper I, are reddened with respect to the models, by amounts that are widely dispersed. Especially for the reddest stars, the displacements are dominated by the known presence of dust in the circumstellar envelope. However, in this respect an additional source of concern is introduced by the poor knowledge of molecular opacities for C-rich atmospheres, and by the fact that they are usually neglected in stellar codes (Marigo et al. 1998). Due to this, it is known that the model effective temperatures of very cool, C-rich AGB models, in the region of thermal pulses, are unreliable and generally largely overestimated. For strongly variable, dynamically perturbed atmospheres the same physical meaning of \( T_{\text{eff}} \) becomes doubtful (Uttenthaler et al. 2007).

Uncertainties in model \( T_{\text{eff}} \) values have very different consequences for the colors of M-type and C-type stars. As an example, let us consider, for AGB stars of the two classes, the effects of a change by 0.1 dex in \( \log T_{\text{eff}} \). For M stars this corresponds, e.g., to moving from type M3 to type M8: the \( (J - K) \) color difference in Figure 4 is less than 0.2 mag. On the contrary, using for C stars the classifications and the color calibrations by Bergeat et al. (2001), we see that the same shift, corresponding, e.g., to moving from the class CV6 to the class CV7 (Bergeat et al. 2002), may imply a color difference \( (J - K) \approx 1 \) (see Fig. 4 in Bergeat et al. 2001). Similar considerations would hold for the \([K - 12.5]\) color in Figure 5. We conclude that while the colors of O-rich AGB stars are not significantly affected by uncertainties in the

---

**TABLE 4**

**SOURCE FLUXES IN THE 2MASS, MSX, AND ISO FILTERS**

| Source No. | Variability Type | \( J \) | \( H \) | \( K \) | 14.6 | 21.3 | Data Origin |
|-----------|-----------------|--------|--------|--------|------|------|-------------|
| 1.......... | P               | 0.01   | 0.02   | 0.01   | 96.3 | 110  | ISO         |
| 2.......... | M               | 0.09   | 1.1    | 6.8    | ...  | ...  | ...         |
| 3.......... | S               | 4.3    | 16.0   | 48.9   | ...  | ...  | ...         |
| 4.......... | P               | <0.01  | 0.03   | 0.20   | 651  | 1260 | ISO         |
| 5.......... | ...             | 0.03   | 0.35   | 62.0   | 51.2 | MSX |
| 6.......... | M               | 0.05   | 0.53   | 3.6    | 227.5| 147.8| MSX         |
| 7.......... | S               | 242    | 495    | 481    | 59.1 | 36.4 | MSX         |
| 8.......... | M               | <0.01  | 0.20   | 2.5    | ...  | ...  | ...         |
| 9.......... | P               | 3.7    | 9.0    | 23.0   | 377  | 472  | ISO         |
| 10.......... | I               | 8.1    | 22.7   | 39.3   | ...  | ...  | ...         |
| 11.......... | P               | 2.9    | 2.1    | 1.5    | 42.0 | 116  | ISO         |
| 12.......... | M               | 2.7    | 74.9   | 469    | 26309| 18194| ISO         |
| 13.......... | S               | 2.5    | 17.1   | 91.4   | ...  | ...  | ...         |
| 14.......... | S               | 641    | 1331   | 1316   | 53.8 | 33.5 | ISO         |
| 15.......... | M               | 9.7    | 27.2   | 82.2   | 91.6 | 54.3 | ISO         |
| 16.......... | S               | 218    | 425    | 464    | 50.4 | 24.7 | ISO         |
| 17.......... | S               | 85.4   | 156    | 143    | 12.7 | 7.8  | MSX         |
| 18.......... | S               | 3065   | 4324   | 3743   | ...  | ...  | ...         |
| 19.......... | M               | 26.3   | 43.4   | 41.4   | ...  | ...  | ...         |
| 20.......... | S               | 804    | 1162   | 1098   | 149  | 104  | ISO         |
| 21.......... | P               | 11.5   | 33.8   | 78.3   | ...  | ...  | ...         |
| 22.......... | S               | 966    | 1448   | 1306   | ...  | ...  | ...         |
| 23.......... | S               | 1145   | 1843   | 1770   | ...  | ...  | ...         |
| 24.......... | I               | 630    | 1033   | 826    | ...  | ...  | ...         |
| 25.......... | S               | ...    | 4210   | 3948   | 584  | 422  | ISO         |
| 26.......... | S               | 512    | 785    | 700    | 76   | 66   | ISO         |
| 27.......... | S               | 3841   | 5627   | 4760   | 273  | 150  | ISO         |

**Note.**—Fluxes are in janskys. Variability types: (M) Mira; (S) semiregular; (I) irregular; (P) post-AGB. Ellipses are for all stars of unknown variability.
atmospheric models, for C stars the situation is worse. At least the less reddened stars in Figure 4 might show displacements from the model areas partly due to the real presence of dust, but partly also induced by errors in model $T_{\text{eff}}$ values, and hence in atmospheric opacities.

A special word of caution must be added for the positions of post-AGB objects in the two plots discussed here. Sometimes they have complex SEDs, related to the fact that the central stars begin to be detached from the circumstellar shells and shine at relatively high temperatures, as typical of a yellow supergiant. In such cases the integral of the IR flux (and in general the procedure described in Paper I) is not sufficient to determine the bolometric magnitude properly, because the optical contribution is not negligible (see, e.g., Kwok et al. 1999, their Fig. 1). For post-AGB objects we therefore have only lower limits to the bolometric magnitudes, which approximate the real values with an error that is different for different cases.

In order to illustrate the cautious remarks made above for the relations between the color excess and the presence of dust, we selected in our sample of TIRCAM2 sources, and in the “best set” of sources in Paper I (those with astrometric distances and very

---

**TABLE 5**

**RELEVANT PARAMETERS AND DISTANCES OF THE SAMPLE STARS**

| Source No. | Variability Type | $\dot{M}$ ($M_\odot$ yr$^{-1}$) | Ref. $v$ (km s$^{-1}$) | Ref. $d$ (kpc) | Ref. |
|------------|------------------|-------------------------------|----------------------|----------------|------|
| 1          | P                | 2.45E-05                      | 1                    | 18.2           | 2.79 | 1 |
| 2          | M                | 1.05E-05                      | 1                    | 12.2           | 1.97 | 1 |
| 3          | S                | 6.33E-06                      | 1                    | 18.5           | 1.03 | 1 |
| 4          | P                | 2.00E-04                      | 2                    | 19.5           | 1.70 | 2 |
| 5          |                  | 1.46E-05                      | 1                    | 20.2           | 2.60 | 1 |
| 6          | M                | 2.40E-05                      | 1                    | 28.0           | 2.01 | 1 |
| 7          | S                | 1.60E-06                      | 3                    | 11.0           | 0.74 | 3 |
| 8          | M                | 1.16E-05                      | 1                    | 15.8           | 1.47 | 1 |
| 9          | P                | 1.00E-04                      | 4                    | 5.0            | 0.71 | 4 |
| 10         | I                | 6.37E-06                      | 1                    | 21.4           | 2.19 | 1 |
| 11         | P                | 2.23E-05                      | 1                    | 10.7           | 2.40 | 5 |
| 12         | M                | 3.30E-05                      | 3                    | 14.7           | 0.15 | 3 |
| 13         | S                | 6.50E-06                      | 3                    | 17.0           | 0.41 | 3 |
| 14         | S                | 1.40E-07                      | 3                    | 8.5            | 0.26 | 3 |
| 15         | M                | 2.30E-06                      | 3                    | 18.4           | 0.68 | 3 |
| 16         | S                | 4.40E-07                      | 3                    | 10.0           | 0.55 | 3 |
| 17         | S                | 6.27E-08                      | 5                    | 8.0            | 0.56 | 5 |
| 18         | S                | (3.92-5.20)E-08               | 5                    | 7.2            | 0.12 | 7 |
| 19         | M                | . . . . . .                    | . . . . . .           | . . . . . .    | . . . . . . | 1.15 | 6 |
| 20         | S                | (4.52-7.21)E-08               | 5                    | 9.1            | 0.31 | 7 |
| 21         | P                | 1.00E-05                      | 1                    | 16.3           | 1.60 | 8 |
| 22         | S                | 5.49E-07                      | 6                    | 7.5            | 0.18 | 7 |
| 23         | S                | 3.70E-07                      | 1                    | 9.3            | 0.14 | 7 |
| 24         | I                | . . . . . .                    | . . . . . .           | . . . . . .    | . . . . . . | 0.14 | 7 |
| 25         | S                | 6.48E-07                      | 1                    | 10.2           | 0.16 | 7 |
| 26         | S                | 5.49E-07                      | 1                    | 8.1            | 0.39 | 7 |
| 27         | S                | 1.43E-07                      | 1                    | 8.5            | 0.11 | 7 |

**Notes.** Variability type: (M) Mira; (S) semiregular; (I) irregular; (P) post-AGB. Ellipses are for all stars of unknown variability.

**References.** Mass loss: (1) Loup et al. 1993; (2) Meixner et al. 1998; (3) Bergeat & Chevallier 2005; (4) Men'shchikov et al. 2002; (5) Groenewegen & de Jong 1998; (6) Winters et al. 2003. Distances: (1) Groenewegen et al. 2002; (2) Meixner et al. 1998; (3) Bergeat & Chevallier 2005; (4) Men'shchikov et al. 2002; (5) Hony et al. 2003; (6) Groenewegen & de Jong 1998; (7) Hipparcos observations; (8) Loup et al. 1993.

---

**Fig. 1.**—Example of a color-color diagram for the observed stars. Big symbols are from TIRCAM2, and small ones are from Paper I. See the text for comments.

**Fig. 2.**—Another example of a color-color diagram for the observed stars. Again, big symbols are from TIRCAM2, and small ones are from Paper I. See the text for explanations.

**Fig. 3.**—Mass-loss rates as a function of the IR colors for the sample of stars in this paper (large circles) and for the best-measured sources of Paper I (small circles). As usual, open symbols refer to S stars, and filled symbols to C stars.
due to the dusty envelope. Spheric flux); the horizontal extension of the data is a measure of the IR excess and in particular for C-rich sources, have temperatures much lower than those predicted: these last, lacking a treatment for C-rich molecular opacities, can be in error by up to 30%.

The effects of absorption features from molecules such as CO, CN, and C2 were shown to be extremely sensitive to the effective temperature and of large consequence for near-IR colors by a hydrostatic analysis of a few C stars (Loidl et al. 2001). The influence of molecular opacities for the changing composition of AGB envelopes gradually enriched by the third dredge-up (TDU) process, and in particular for C-rich sources, was also addressed by Marigo (2003). She showed how a large decrease in $T_{\text{eff}}$ can be induced by the inclusion of opacities from molecules made of CNO and hydrogen. In models of about 2 $M_\odot$, a shift in log $T_{\text{eff}}$ of almost 0.1 dex can be obtained (see Fig. 6 in that paper). Just as an example, by reducing by this amount the temperatures of the model tracks in Figure 6 (in order to simulate the effect of molecular opacities), we get the curves at the right side of the plot (those with crosses superposed). It is evident that a proper atmospheric model might in many cases be sufficient to yield the values of $T_{\text{eff}}$ derived from observations. We warn that the new tracks must be seen only as a rough example, plotted for illustration purposes. In fact, Marigo (2003) computed a synthetic AGB evolution (while the tracks in Fig. 6 were derived from complete AGB models), and her assumptions for dredge-up were rather different from those in the models we used (Straniero et al. 2003). What one would really need here is a set of complete AGB models, including a proper treatment of surface opacities for the changing envelope composition during the TDU process, something that unfortunately does not exist yet.

The above discussion says that, for C stars, disentangling the atmospheric opacity effects from the color excess due to dust will become quantitatively meaningful only with large samples of good mid-IR observations, determining the properties of dust for sources for which $T_{\text{eff}}$ has been independently determined (e.g., from spectra). This in its turn would help stellar modelers to construct more detailed opacity tables, calibrated on observations. This is a relevant target to be pursued. In fact, the compilation of accurate IR catalogs was started by several groups years ago (see, e.g., van Loon et al. 1999; Cioni et al. 2001; Le Bertre et al. 2001). It has continued to be an essential tool in recent years (Bergeat et al. 2002; Le Bertre et al. 2003; Cioni et al. 2003) and remains important now (Bergeat & Chevallier 2005; Le Bertre et al. 2005; Whiteoak et al. 2006). It will also be one of the key projects of the Antarctic telescope IRAIT (International Robotic Antarctic Infrared Telescope) that we recently developed and that will be operational at the Italo-French base of Dome C starting in the 2007–2008 Antarctic campaign (see, e.g., Tosti et al. 2006; Busso et al. 2007).

5. INFRARED VARIABILITY

Figures 7 and 8 show the available information on the IR SEDs for two groups of sources in the list of Table 1. The plots include...
data from the *IRAS* PSC (Point Source Catalog), *IRAS* LRS (Low Resolution Spectrometer), *ISO*, and MSX, together with our TIRCAM2 measurements. Figure 7 shows distributions that, despite their different appearance, share the property of being nonvariable over a time interval of almost 20 years. The figure contains rather heterogeneous measurements: photometric data (from the *IRAS* PSC, MSX, and our ground-based observations) are compared with spectroscopic information from the *ISO* SWS and *IRAS* LRS. For our purposes this is sufficient: as verified in Paper I, the proper convolution of *ISO* SWS and *IRAS* LRS spectra with the response of our filters, yielding a homogeneous photometric database, would not affect the flux levels by more than 5%, which is well inside the internal uncertainty of each set of data used. A constancy of the IR energy distribution is the more common behavior displayed by our sources, being shared by exactly two-thirds of the AGB stars in our sample (18 out of 27). This property characterizes stars that are very different from one another. They include sources with minimal IR excess (usually semiregular variables), in which the SED is peaked in near-IR, but they also include evolved (post-AGB) objects, in which the maximum emission is at very long wavelengths (from 20 to more than 40 μm) due to the dominant effects of cold, distant dust.

In contrast, Figure 8 shows the behavior of intermediate objects, usually Mira variables, in which the emission peaks near 10 μm (and sometimes is rather flat up to about 20 μm), efficiently powering the typical features there present for O-rich and C-rich dust. Nine sources share this behavior (RAFGL sources 190, 809, 865, and 954, IRC +60144, RU Vir, CIT 6, CW Leo, and IRC +40156). It seems, therefore, that long-term mid-IR variability is not a common property of AGB stars but is restricted to a special class of sources in the special evolutionary stage when most of the flux is reradiated by circumstellar layers of 1 to a few hundred K. Here stellar pulsation (which is of large amplitude in the optical bands) should effectively transfer energy to dust shells, which are quite opaque down to the mentioned temperatures. One can guess that this is the phase in which the coupling between the photosphere and the circumstellar envelope is most efficient: for bluer sources, not enough dust is created, probably because of a mass-loss rate that is still not strong enough. For redder objects, circumstellar dust becomes cold and distant, probably detaching itself from the central star.

One might a priori argue that the semiregular sources might look stable only because of their small IR fluxes: when the flux is very low any variability might be more difficult to disentangle from the background noise. In order to make our suggestions more secure, we looked for sources (both variable and nonvariable) for which the *ISO* SWS offered repeated observations. We found a few interesting cases. Examples are presented in Figure 9 for the C-rich semiregular star S Scl and for the C-rich Mira variable V Cyg. Even looking in the figure only at homogeneous data sets (those from *ISO*, covering about 2 years), our previous suggestions seem to be confirmed. It is indeed clear that the Mira variable does vary as we mentioned, and it can also be understood how the nonvariability of S Scl in mid-IR in the time interval...
Fig. 8.—SEDs of sources that show significant variability over the time elapsed from the IRAS to the TIRCAM2 observations. Again, data obtained with TIRCAM2 and data available from the IRAS PSC and the IRAS LRS, ISO SWS, MSX, and 2MASS catalogs are included. Only sources for which the emission is maximum in the range 8–20 μm appear to be variable, independently of their composition (C-rich or O-rich).
covered by the $ISO$ data (at a level better than 10%) does not come from insufficient precision, since the minimum flux is on the order of tens of janskys.

The idea that the variable sources are those for which radiation pressure on dust grains powers mass loss suggests itself, although we can look at this only as a tentative interpretation, because the source statistics and also the number of available points per source are rather limited. This hypothesis deserves now to be verified through modeling of the radiation transfer in the dust-condensing envelope, and it should also be determined whether IR variability corresponds to a specific evolutionary stage or can be encountered repeatedly (the same dilemma presented by optical Mira variability).

6. CONCLUSIONS

The data presented in this note confirm the usefulness of mid-IR colors taken from ground-based telescopes in describing the properties of mass-losing AGB stars. Our photometric study yields results compatible with those of Paper I, and begins to extend the analysis to a number of O-rich (S and M) sources. These will now be the object of dedicated papers based on a large observational database of space-borne telescope data, similar to Paper I.

In general we showed how, for most semiregular variables and post-AGB stars, the IR fluxes longward of a few microns are insensitive to variations in the stellar photosphere and remain essentially constant in time over rather long time intervals (tens of years). However, this does not apply to Mira variables, and in general to AGB sources with maximum emission near 10 $\mu$m. Such objects show remarkable variability in emission/absorption features (with changes from emission to absorption and back) and/or global flux, showing that warm dust quickly reacts to large-amplitude surface pulsations, with large changes in concentration and temperature. This might suggest that dust-driven winds are mainly associated with the Mira variable stage, a hypothesis to be further verified.

Our results also point out how urgent it is to match stellar evolutionary codes with reliable model atmospheres, especially for C stars, including molecular opacities. This would allow one to reliably predict the effective temperature of C-rich atmospheres, and hence to give a quantitative meaning to the IR color excess in terms of dust emission, without remaining uncertainties from poorly understood photospheric opacities.

M. B. and R. G. acknowledge support by MIUR (contract PRIN2004-025729) and by the PNRA (within the IRAIT project). R. G. acknowledges the University of Perugia for a postdoctoral fellowship. TIRCAM2 was operated by IASF-CNR and by the Observatory of Torino (both are now part of INAF). Special thanks go to A. Ferrari for supporting the TIRCAM2 project during his term as a director of the Torino Observatory. This research made use of the SIMBAD database, of the VizieR service (CDS, Strasbourg, France), and of the Astrophysics Data System of NASA. In particular, archived data from the Midcourse Space Experiment, Infrared Space Observatory SWS, and Two Micron All Sky Survey were used. (The processing of the science data from the MSX was funded by the US Ballistic Missile Defense Organization, with additional support from the NASA Office of Space Science. The $ISO$ was an ESA project with instruments funded by ESA member states [especially the principal investigator countries: France, Germany, the Netherlands, and the United Kingdom] and with the participation of the Institute of Space and Astronomical Science and NASA. 2MASS was a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center at the California Institute of Technology; it was funded by NASA and by the NSF [USA]).

REFERENCES

Cioni, M.-R. L., et al. 2003, A&A, 406, 51
Cohen, M., Walker, R. G., Carter, B., Hammersley, P., Kidger, M., & Noguchi, K. 1999, AJ, 117, 1864
Corcione, L., Busso, M., Porcu, F., Ferrari-Toniolo, M., & Persi, P. 2003, Mem. Soc. Astron. Italiana, 74, 57
Feast, M. W. 2007, in ASP Conf. Ser., Why Galaxies Care about AGB Stars, ed. F. Kerschbaum, C. Charbonnel, & R. Wing (San Francisco: ASP), in press
Feast, M. W., White洛克, P. A., & Menzies, J. W. 2006, MNRAS, 369, 791
Groenewegen, M. A. T., & de Jong, T. 1998, A&A, 337, 967
Groenewegen, M. A. T., Sevenster, M., Spoon, H. W. W., & Perez, I. 2002, A&A, 390, 511

Fig. 9.—$ISO$ SWS SEDs of two carbon stars: a Mira variable (top) and a semiregular variable (bottom). They were observed repeatedly by $ISO$ over about 2 years. On this rather short timescale, but with homogeneous data, our suggestions about the mid-IR variability of Mira variables and the flux constancy of semiregular variables seem to be confirmed.
Guandalini, R., Busso, M., & Cardinali, M. 2007, in ASP Conf. Ser., Why Galaxies Care about AGB Stars, ed. F. Kerschbaum, C. Charbonnel, & R. Wing (San Francisco: ASP), in press
Guandalini, R., Busso, M., Ciprini, S., Persi, P., & Silvestro, G. 2006, A&A, 445, 1069 (Paper I)
Habing, H. J. 1996, A&A Rev., 7, 97
Herwig, F. 2005, ARA&A, 43, 435
Hony, S., Tielens, A. G. G. M., Waters, L. B. F. M., & de Koter, A. 2003, A&A, 402, 211
Jura, M. 1986, ApJ, 303, 327
Jura, M., & Kleinmann, S. G. 1989, ApJ, 341, 359
Kwok, S., Vols, K., & Hrivnak, B. J. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lebre, & C. Waelkens (San Francisco: ASP), 297
———. 2002, ApJ, 573, 720
Le Bertre, T., Matsuura, M., Winters, J. M., Murakami, H., Yamamura, I., Freund, M., & Tanaka, M. 2001, A&A, 376, 997
Le Bertre, T., Tanaka, M., Yamamura, I., & Murakami, H. 2003, A&A, 403, 943
Le Bertre, T., Tanaka, M., Yamamura, I., Murakami, H., & MacConnell, D. J. 2005, PASP, 117, 199
Leech, K., et al. 2004, The ISO Handbook, Vol. V, Ver. 2.0.1 (Noordwijk: ESA)
Loidl, R., Lançon, A., & Jørgensen, U. G. 2001, A&A, 371, 1065
Loup, C., Forveille, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291
Marigo, P. 2003, in ASP Conf. Ser. 304, CNO in the Universe, ed. C. Charbonnel, D. Schaerer, & G. Meynet (San Francisco: ASP), 312
Marigo, P., Bressan, A., & Chioffi, C. 1998, A&A, 331, 564
Meixner, M., Campbell, M. T., Welch, W. J., & Likkel, L. 1998, ApJ, 509, 392
Men'shchikov, A. B., Schertl, D., Tuthill, P. G., Weigelt, G., & Yungelson, L. R. 2002, A&A, 393, 867
Menzies, J. W., Feast, M. W., & Whitelock, P. A. 2006, MNRAS, 369, 783
Olofsson, H., Eriksson, K., Gustafsson, B., & Carlstrom, U. 1995a, ApJS, 87, 267
———. 1993b, ApJS, 87, 305
Persi, P., et al. 1994, Exp. Astron., 5, 363
———. 2002, in Solids and Molecules in Space, ed. S. Aiello, B. Barsella, & C. Cecchi-Pestellini (Bologna: Italian Phys. Soc.), 205
Sedlmayr, E. 1994, in Molecules in the Stellar Environment, ed. U. G. Jørgensen (Berlin: Springer), 163
Stetson, P. B. 1987, PASP, 99, 191
Straniero, O., Chieffi, A., Limongi, M., Busso, M., Gallino, R., & Arlandini, C. 1997, ApJ, 478, 332
Straniero, O., Domínguez, I., Cristallo, S., & Gallino, R. 2003, Publ. Astron. Soc. Australia, 20, 389
Tost, G., et al. 2006, Proc. SPIE, 6267, 47
Uttenthaler, S., Hrin, J., Lebzelter, T., Busso, M., Shultheis, M., & Käufl, H.-U. 2007, A&A, 463, 251
van Leeuwen, F. 2005, A&A, 439, 805
van Leeuwen, F., & Fantino, E. 2005, A&A, 439, 791
van Looij, J. Th., Cioni, M.-R. L., Zijlstra, A. A., & Loup, C. 2005, A&A, 438, 273
van Looij, J. Th., Groenewegen, M. A. T., de Koter, A., Trams, N. R., Waters, L. B. F. M., Zijlstra, A. A., Whitelock, P. A., & Loup, C. 1999, A&A, 351, 559
van Looij, J. Th., Zijlstra, A. A., Kaper, L., Gilmore, G. F., Loup, C., & Blommaert, J. A. D. L. 2001, A&A, 368, 239
Whitelock, P. A., Feast, M. W., Marang, F., & Groenewegen, M. A. T. 2006, MNRAS, 369, 751
Winters, J. M., Le Bertre, T., Jeong, K. S., Nyman, L.-Å., & Epechtein, N. 2003, A&A, 409, 715
Winters, J. M., Le Bertre, T., Nyman, L.-Å., Omont, A., & Jeong, K. S. 2002, A&A, 388, 609
Zhang, K., Jiang, B.-W., & Li, A.-G. 2006, Prog. Astron., 24, 43
Zijlstra, A. A., et al. 2006, MNRAS, 370, 1961