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Mary Ann Hickman
Swarthmore College, mklasse1@swarthmore.edu

G. C. Sloan

R. Canterna

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AN INFRARED COLOR–MAGNITUDE RELATIONSHIP

M. A. Hickman[1]
Department of Physics and Astronomy, University of Wyoming, Laramie, Wyoming 82071
Electronic mail: hickman@sparky.uwyo.edu

G. C. Sloan
NASA Ames Research Center, MS 245-6, Moffett Field, California 94035-1000
Electronic mail: sloan@ssa1.arc.nasa.gov

R. Canterna
Department of Physics and Astronomy, University of Wyoming, Laramie, Wyoming 82071
Electronic mail: canterna@uwyo.edu

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ABSTRACT

We have investigated a sample of dusty supergiants and Mira variables and have found a roughly linear relationship between the absolute magnitude at 12 μm and the [12]–[25] color. Both samples follow the same infrared color–magnitude relationship, which may serve as a distance indicator and a means of better understanding the mass-loss and dust-formation mechanisms of evolved stars. © *1995 American Astronomical Society.*

1. INTRODUCTION

The importance of luminous red giants and supergiants as distance indicators has long been recognized (Sandage & Tammann 1974). While these stars have been used to find distances to external galaxies (e.g., Humphreys 1979), much of what is in the Galactic plane, especially toward the Galactic center, is obscured at optical wavelengths. Infrared radiation penetrates the dust that blocks visible light, and bright red giants and supergiants are even more luminous in the infrared than they are in the optical regime. Therefore, a method of determining the distance to these bright evolved stars in the infrared would provide an extremely valuable probe of the structure of our own Galaxy.

The *Infrared Astronomical Satellite* (*IRAS*) observed virtually the entire sky at mid- to far-infrared wavelengths, making the *IRAS* Point Source Catalog (1987; hereafter referred to as PSC) an excellent database for the study of bright evolved stars. We have examined the 12 and 25 μm fluxes for a set of evolved stars associated with circumstellar dust and have found a relationship between the absolute magnitude of a source at 12 μm and its infrared color. In Sec. 2, we define our sample of supergiants and Mira variables and describe how we estimate the distances to these sources. The membership of supergiants in OB associations and the period–luminosity relationships for Mira variables make distance determinations for both of these groups straightforward. In Sec. 3, we discuss the color–magnitude relationship revealed by our investigation.

2. OBSERVATIONAL DATA

2.1 Background

All of our measurements at 12 and 25 μm are taken from the PSC. We define the magnitudes

$$[12]=-2.5\ \log(f_{12\ \mu\mathrm{m}}/28.3\ \mathrm{Jy}),$$

$$[25]=-2.5\ \log(f_{25\ \mu\mathrm{m}}/6.73\ \mathrm{Jy}),$$

$$[60]=-2.5\ \log(f_{60}\ \mu\mathrm{m}/1.19\ \mathrm{Jy}),$$

and the colors

$$[12]-[25]=1.56+2.5\ \log(f_{25\ \mu\mathrm{m}}/f_{12\ \mu\mathrm{m}}),$$

$$[25]-[60]=1.88+2.5\ \log(f_{60\ \mu\mathrm{m}}/f_{25\ \mu\mathrm{m}}).$$

Some authors (e.g., Van der Veen & Habing 1988) define their infrared colors without the additive constants which account for the zero magnitude fluxes.

2.2 Supergiants

The supergiants used in this study are all members of OB associations. These loose groupings of stars consist of very young stars, generally massive O and B stars on the order of a few million years old. There are, however, a small number of late-type supergiants among association members. They are most likely the first stars in the associations to move off the main sequence.

Our sample of supergiants was taken from the study of Stencel *et al.* (1989) which provides a table of 111 supergiants of spectral types F through M taken from Humphreys's catalog of galactic supergiants (1978). We selected a subset of this sample, choosing supergiants within a range of colors 1.17–1.77 in [12]–[25] and −0.52–0.88 in [25]–[60]. Most of the sources in this region of the color–color diagram are associated with mass loss and are long-period variables

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[1] Current address: Department of Physics and Astronomy, Swarthmore College, Swarthmore, PA 19081.

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TABLE 1. Supergiants.

IRAS	Name	[12]-[25]	$\sigma_{[12]-[25]}$	M_{12}[a]	D (pc)
00464+6430	Case 23	0.93	0.06	-11.1	3750
01051+6319	HS Cas	1.17	0.06	-13.9	6490
01435+6007	HD 236871	0.77	0.06	-10.8	3090
01550+5901	HD 236915	0.70	0.06	-11.0	2780
02068+5619	KK Per	0.93	0.06	-11.1	2000
02116+5754	HD 13658	0.52	0.06	-10.4	3150
02135+5817	PP Per	0.47	0.08	- 9.8	2570
02153+5711	BU Per	1.17	0.06	-11.9	1870
02157+5843	T Per	1.16	0.06	-11.2	2870
02167+5926	HD 14242	1.21	0.06	-10.9	2290
02169+5645	AD Per	1.10	0.06	-11.3	2130
02174+5655	FZ Per	0.63	0.06	-10.7	2220
02181+5738	PR Per	1.22	0.06	-10.7	2040
02185+5622	SU Per	1.06	0.06	-12.4	2320
02185+5652	RS Per	1.08	0.06	-13.4	2980
02217+5712	HD 14826	1.20	0.12	-11.3	2290
02347+5649	YZ Per	1.13	0.12	-12.2	2310
02360+5922	GP Cas	1.20	0.12	-11.9	2500
02469+5646	W Per	1.41	0.12	-14.4	4310
05239+2952	HD 35601	0.42	0.12	- 9.6	1220
05374+3153	HD 37536	0.86	0.12	-10.7	1130
06088+2152	TV Gem	0.64	0.16	-11.5	1080
06092+2255	BU Gem	1.02	0.12	-12.7	2040
06520-2407	o^1 CMa	0.54	0.12	- 9.1	570
07390-3133	CD-31°4916	1.14	0.12	-12.1	4310
10226-5956	CK Car	1.04	0.12	-13.5	2512
11113-5949	HD 97671	0.78	0.12	-13.5	1995
13141-6119	V396 Cen	1.24	0.12	-13.7	2512
15576-5400	HD 143183	0.94	0.12	-14.8	2500
17488-2800	KW Sgr	0.99	0.12	-14.8	3020
19480+2447	BD+24°3902	0.92	0.12	-13.1	2110
20194+3646	BI Cyg	1.13	0.12	-14.0	1819
20241+3811	KY Cyg	1.08	0.12	-14.7	2060
20270+3948	RW Cyg	1.07	0.12	-13.0	1202
21419+5832	μ Cep	0.74	0.12	-13.0	580
22212+5542	RW Cep	1.49	0.12	-14.0	3467
22282+5644	ST Cep	1.10	0.12	-10.3	832
22456+5453	U Lac	0.80	0.06	-14.3	3467
23080+6058	GU Cep	0.85	0.10	-11.0	3080
23416+6131	PZ Cas	1.63	0.10	-15.2	3090
23504+6043	TZ Cas	1.16	0.06	-13.3	2780

[a] all uncertainties in M_{12} are 0.3

TABLE 2. Mira variables.

IRAS	Name	[12]-[25]	$\sigma_{[12]-[25]}$	M_{12}[a]	P (d)	K	D (pc)
00042+4248	KU And	1.14	0.09	-14.0	750	2.20	1510
00205+5530	T Cas	0.61	0.09	- 9.8	445	-1.10	230
02168-0312	o Cet	0.72	0.09	-10.4	332	-2.70	90
02522-5055	R Hor	0.64	0.09	-10.2	408	-1.10	220
03507+1115	IK Tau	0.84	0.09	-12.9	470	-0.70	290
03500+0829	GX Mon	1.00	0.15	-12.4	527	0.85	650
04566+5606	TX Cam	0.53	0.24	-12.1	557	-0.55	350
05132+5331	R Aur	0.56	0.09	-10.1	458	-0.95	260
05528+2010	U Ori	0.51	0.09	-10.4	368	-0.75	240
09309-6234	R Car	0.45	0.07	- 9.2	309	-1.20	170
09425+3444	R LMi	0.60	0.15	-10.2	372	-0.45	280
09429-2148	IW Hya	1.34	0.09	-13.9	650	2.10	1320
09448+1139	R Leo	0.26	0.17	- 9.7	310	-2.45	100
13269-2301	R Hya	0.48	0.09	- 9.6	389	-2.50	110
18349+1023	V1111 Oph	0.67	0.13	-11.1	234	0.60	330
18560-2954	V3953 Sgr	0.84	0.23	-12.7	405	1.55	740
16235+1900	U Her	0.45	0.13	-10.9	406	0.00	360
18359+0847	X Oph	0.44	0.09	- 9.5	329	-0.85	210
19039+0809	R Aql	1.02	0.22	- 9.4	284	-0.70	200
19093-3256	V342 Sgr	1.11	0.13	-11.7	372	1.20	590
19550-0201	RR Aql	0.70	0.13	-10.7	395	0.30	410
21088+6817	T Cep	0.43	0.09	- 9.7	388	-1.60	170
23412-1533	R Aqr	0.40	0.09	-11.4	387	-0.60	260
23558+5106	R Cas	0.60	0.09	-10.1	430	-2.00	150

[a] all uncertainties in M_{12} are 0.5

(of type SRc or Lc; Van der Veen & Habing 1988; Hoffmeister *et al.* 1984). Table 1 presents our sample of supergiants.

When available, distances to the supergiants were taken from Humphrey's earlier catalog of supergiants (1970). Otherwise, we used the distance to the star's OB association (Lang 1992; Zombeck 1990) to calculate the distance modulus and thus M_{12}, the absolute magnitude at 12 μm.

2.3 *Mira Variables*

Miras are long-period variables usually associated with mass loss and circumstellar dust shells. They occupy the asymptotic giant branch (AGB) on the HR diagram, and their progenitors have lower masses than the supergiants (only ~1-2 $\mathscr{M}_\odot$). Mira variables pulsate more steadily than supergiants, making their period of variability easier to define. Sloan & Price (1995) obtained a sample of bright infrared Miras by cross referencing the *General Catalog of Variable Stars* (*GCVS*; Kholopov *et al.* 1985–88) and the PSC. We have examined 24 of the 25 brightest sources at 12 μm from this sample; they are listed in Table 2. (One source, R Cen, was rejected from our sample because of large *IRAS* uncertainties.)

To determine the distance to the Mira variables, we use the period–luminosity relation first defined by Feast *et al.* (1989) for the Large Magellanic Cloud and modified for the metallicity of the galaxy (Wood 1990; Jura & Kleinmann 1992):

$$M_K = -3.47 \log P + 1.26,$$

where P is the period in days. Using the periods given in the *GCVS* we obtain the absolute K magnitude. We averaged the available ground-based photometry (Jones *et al.* 1990; Catchpole *et al.* 1979; Gezari *et al.* 1987) to obtain an estimate of the mean apparent magnitude at K and thus a distance modulus.

2.4 *Uncertainties*

One source of error in the absolute magnitudes and colors arises from the *IRAS* measurements. The PSC describes the errors for the broadband photometry using flux quality flags which correspond to a range of uncertainties (i.e., $A=0\%$ to 4%, $B=4\%$ to 8%, etc.). We take the average value in each uncertainty range as the percent uncertainty in the flux. For example, if a source's 12 μm flux quality flag is "B," then the uncertainty is 6% of the 12 μm flux.

The variability of these objects introduces additional error. All of our sources were sampled by *IRAS* more than once, but this is no guarantee that the time-averaged photometry will equal the mean magnitude at 12 μm. The light curves and amplitude of variability at 12 μm are not well studied, so we are unable to quantify this error. We have not attempted to correct for this source of error or include it in our estimated uncertainties.

We combined errors in distance modulus (and thus M_{12}) with the errors based on the *IRAS* quality flags. For the supergiants, we estimate the error in distance as 15%, which results in an error of 0.33 mag in distance modulus and M_{12}.

We estimate the error in distance modulus for the Mira variables to be 0.5 mag, based on two contributing factors. Most of the Mira variables observed by Catchpole *et al.* (1979) over a sufficient portion of the light curve to define the K amplitudes show that ΔK~0.8 mag, so any single photometric measurement must be within ~0.4 mag of the mean K magnitude. A further error of 0.2 mag could result from the spread of the period–luminosity relationship as measured by Feast *et al.* (1989) for the LMC.

We did not attempt to estimate an additional source of systematic error in the distances to Miras. Feast *et al.* (1989) fit a line to the dependence of $\langle K \rangle$ on log P as observed in

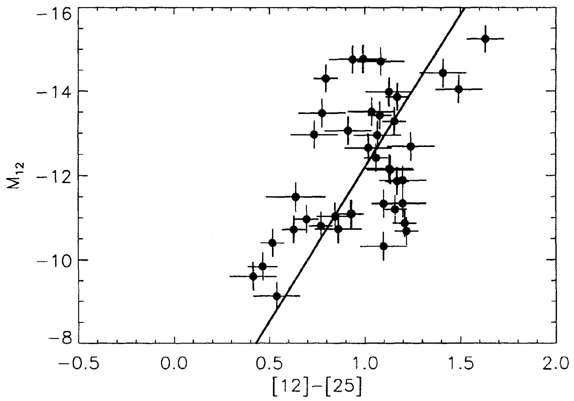

FIG. 1. The color–magnitude relationship for the supergiant sample. The line is the two-dimensional weighted least-squares fit for supergiants given in Table 3.

the Large Magellanic Cloud, but long-period Miras deviate from this line. As they illustrate, Miras with periods around 600 days are brighter than the derived linear relation by about half a magnitude. Because of the AGB–luminosity limit, extremely long-period variables will actually be *fainter* than predicted by a linear relation of M_K on the log of the period (Wood *et al.* 1992; 1983). Because these deviations from linearity are not well quantified, and because they may be different for our galactic sources of higher metallicity, we have not attempted to correct for them. We note that only two of the Miras in our sample have periods longer than 600 days, and most have periods less than 400 days. Our determinations of M_{12} for the reddest sources in our sample may be overestimated by half a magnitude; this will have no effect on our conclusions below.

We also considered the effect of interstellar extinction when calculating M_{12}. Mathis (1990) presented a general extinction law in the form of the ratio A_λ/A_J, which is independent of distance for $\lambda \geqslant 0.9$ μm. A_V is known for our sources (Humphreys 1978), so we used Mathis's data to make estimates of corrections to the 12 and 25 μm distance moduli, which are

$$A_{12}/A_V=0.028$$

and

$$A_{25}/A_V=0.014.$$

The largest A_V in the sample was 6.88 mag for KY Cyg, yielding $A_{12} = 0.19$ mag and $A_{25} = 0.10$ mag. More typically, A_V ranged from about 1.5 to 3.0 mag, giving a range of 0.04–0.08 mag for A_{12} and 0.02–0.04 mag for A_{25}. These corrections are very small, so we can safely ignore interstellar extinction at mid-infrared wavelengths.

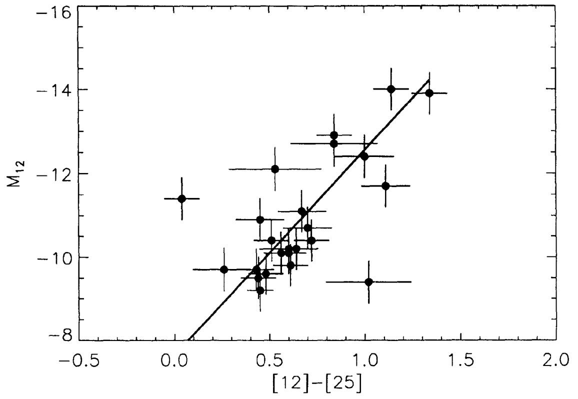

FIG. 2. The color–magnitude relationship for the Mira sample. The parameters of the best-fit line for Mira variables are given in Table 3.

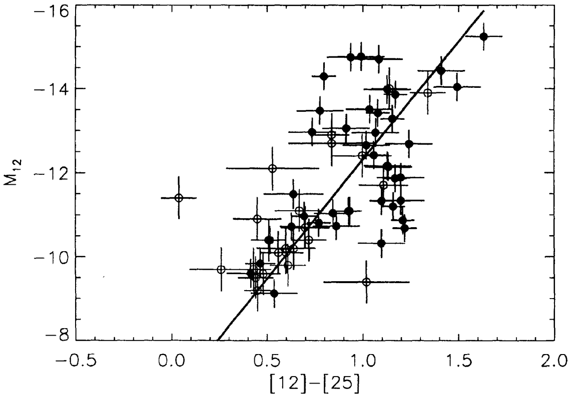

FIG. 3. The color–magnitude relationship for the combined sources. Supergiants are represented by closed circles; Miras by open circles.

3. DISCUSSION

Figures 1 and 2 present the resulting infrared color–magnitude diagrams for supergiants and Mira variables, respectively. The sources in both samples show a correlation between M_{12} and [12]–[25] color, with redder sources being brighter. Figure 3 demonstrates that both samples *follow the same relationship.* To quantify this color–magnitude relation, we have fit a line to the data, using a weighted two-dimensional least-squares method. We calculate weighted fits for the supergiants and Mira variables separately and for the sources combined, and give the results in Table 3.

A relationship between M_{12} and [12]–[25] for Mira variables is not completely unexpected. De-Gioia-Eastwood *et al.* (1981) discovered that the [8.7]–[11.4] color, which they used to measure the strength of circumstellar silicate emission, increased monotonically as the period increased. Jones *et al.* (1990) found a similar relation with *K–L*. Since

TABLE 3. Parameters of linear least-squares fits.

$M_{12} = a \times ([12]-[25]) + b$

sample	a	b
supergiants	-7.30 ± 0.65	-4.88 ± 0.65
Miras	-4.90 ± 0.62	-7.65 ± 0.44
combined	-5.65 ± 0.33	-6.65 ± 0.31

the total luminosity of a Mira variable increases with period, one would expect that brighter Mira variables would also be redder at [12]–[25].

While supergiants also follow a period–luminosity relation, it is shifted to higher luminosities (Wood *et al.* 1983, 1992). One would expect the luminosity class of the star to influence the strength of the mid-infrared emission, so it is surprising that both supergiants and Mira variables (giants) follow the same infrared color–magnitude relation. Naked stars will not follow this relationship, since they will all cluster around [12]–[25] colors of zero and the differences in luminosities and temperatures will produce a substantial spread in M_{12}. We conclude that the properties of the circumstellar dust are dominating the properties of the stars at these wavelengths and are responsible for the relation we have uncovered.

While the data do reveal a roughly linear correlation between M_{12} and [12]–[25] color, the scatter of the data about this relationship is substantial. The error bars may account for much of this scatter, but the errors may be overestimated. On the other hand, we have not included any estimate of errors in 12 μm photometry due to variability of the sources during the *IRAS* epoch. Until the uncertainties in the distances and the *IRAS* measurements are reduced, it is impossible to state whether the spread in our color–magnitude relation results from noise in the data or arises from intrinsic differences among the sources in our sample. We can only state that a relationship between the [12]–[25] color and the absolute magnitude at 12 μm does exist for stars with circumstellar dust.

In the most accepted evolutionary scenario, stars ejecting their envelopes evolve from naked stars to infrared sources encased within circumstellar dust shells of steadily increasing optical depth. Their [12]–[25] color would increase from zero to about 2.5 before the shell becomes detached and the source develops into a planetary nebula (Bedijn 1987; Van der Veen & Habing 1988). Within this context, our color–magnitude relation may reveal the evolutionary tracks of these sources and may represent the infrared analog of the HR diagram.

Ultimately, the color–magnitude relation may serve as a distance indicator, but the present uncertainty in the linear fit limits its utility for this purpose. If subsequent investigation reveals that all sources do indeed follow a tight correlation between color and infrared luminosity, this would prove to be a very powerful tool for understanding galactic structure.

The spread in the data may result from real differences between sources. It could result from the chemistry of the dust or from differing luminosities of the central sources, which would in turn depend on the progenitor mass and metallicity. In this case it would be necessary to know something else about the nature of the system before its distance could be determined. To turn this around, using the color–magnitude relation for a source whose distance is known may reveal important information about its origin.

4. CONCLUSION

Using *IRAS* photometry, we have found an approximately linear relationship between 12 μm absolute magnitude and [12]–[25] color for Mira variables and supergiants with dust shells. One relationship fits both samples of stars. This relationship may have application in finding distances to stars with circumstellar dust in the Galaxy. It may also represent the beginnings of an infrared stellar evolutionary track. Further study of a larger and more diverse sample of stars will test the validity of these hypotheses.

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