Infrared and Pulsation Properties of Galactic-Plane O- and C-rich Miras

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Introduction

- Mira variables are mass-losing, pulsating late-type giants at the top of the Asymptotic Giant Branch.
- These dust-enshrouded stars are very red, hence infrared (IR) observations are important in their study.
- Near-IR (1.2, 1.6, 2.2, 3.5 μm) photometry observations obtained at the South African Astronomical Observatory (SAAO) are used to study the properties of a sample of $IRAS$ Miras.

Introduction

- The near-IR, mid-IR (12, 25 μm) data from *IRAS* and limited data from the literature are used to demonstrate the $K - L$ vs. $[12\,\mu\mathrm{m}] - [25\,\mu\mathrm{m}]$ two-color classification of Miras as oxygen-rich and carbon-rich (due to the opacity of their shells), without (prior) spectral observations.
- The two groups of Miras are separated and their stellar, circumstellar and pulsation properties are compared and analyzed in detail.

Outline of Project Goals

- Determine periods and amplitudes of Miras, and exclude non-Miras
- Classify the Miras into O-rich and C-rich stars, based on their colors
- Compare the O-rich and C-rich period and amplitude distributions
- Investigate the Mira pulsations in relation to the color-indicators of their stellar temperatures and dust-shell physical properties

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(work not presented here)

- Determine the stars' bolometric magnitudes, radial (d) and galactic-plane (z) distances and mass-loss characteristics
- Determine galactic distributions of the O-rich and C-rich Miras and relate these to the Mira properties above
- Answer relevant statistical and astrophysical questions about the stars in the contexts of Mira dust contribution or recycling of the ISM

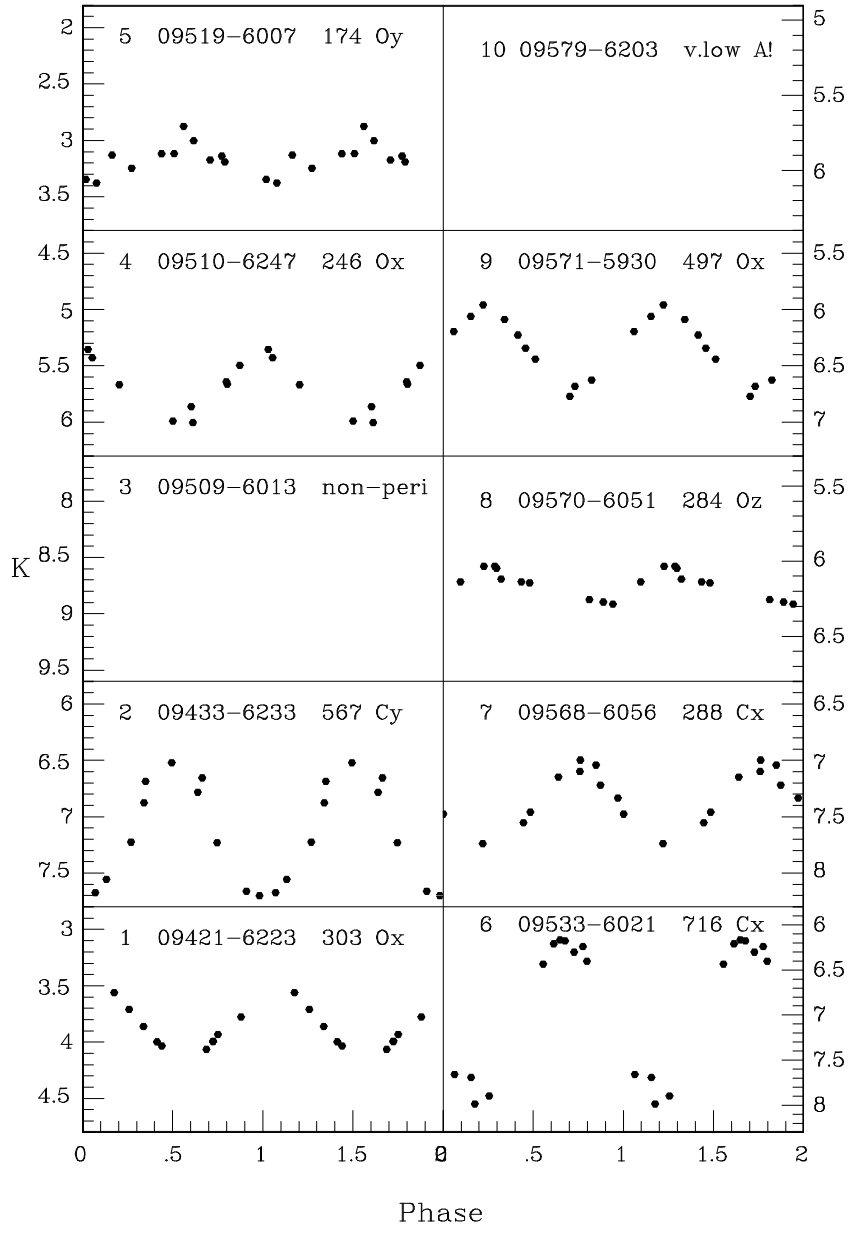
Observations

- Using the Mk III photometer on the SAAO 1.9 m telescope, over 1090 $JHKL$ observations were obtained for 101 *IRAS* sources.
- The objects were expected to be Miras, on the basis of their *IRAS* colors, and that lie in a region of moderate interstellar extinction close to the galactic plane: $-7.^\circ3 < b < +1^\circ$ and $282.^\circ5 < l < 285.^\circ5$.
- The magnitude accuracies were $JHK \sim 0.03$ and $L \sim 0.05$ mag.
- Based on the photometry, the sample has been shown to comprise 85 Miras, 12 of which had published periods.

Observations

- New periods were determined for the 85 Miras at an accuracy of ± 15 days for periods less than 550 days and ± 25 days for longer periods.
- We show some phased K light curves as a function of phase for the variables, illustrating the variety in accuracies of stellar period and amplitude, depending on the number of observations, light curve shape, and the cycles' repeatability.
- In the diagram, each point is plotted twice and the choice of zero phase is arbitrary.

K light curves as a function of phase



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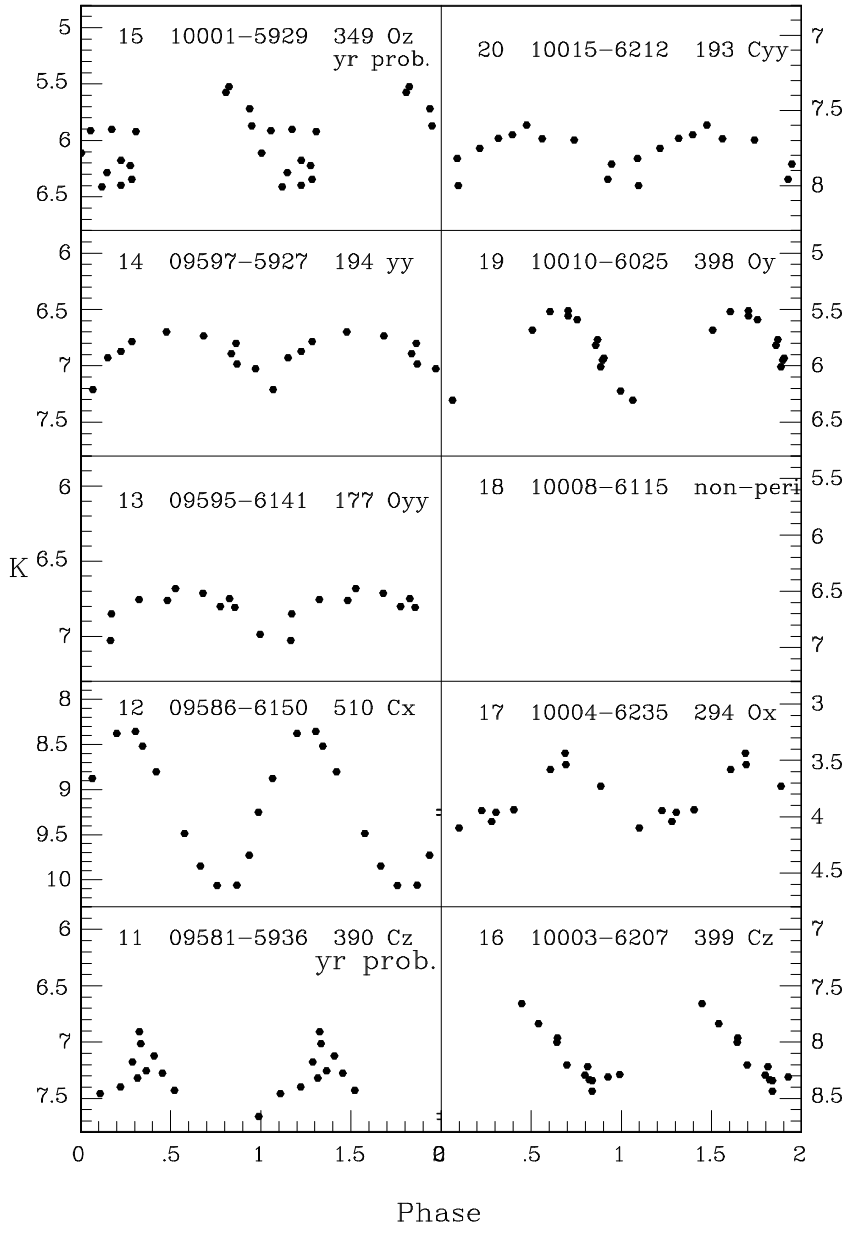


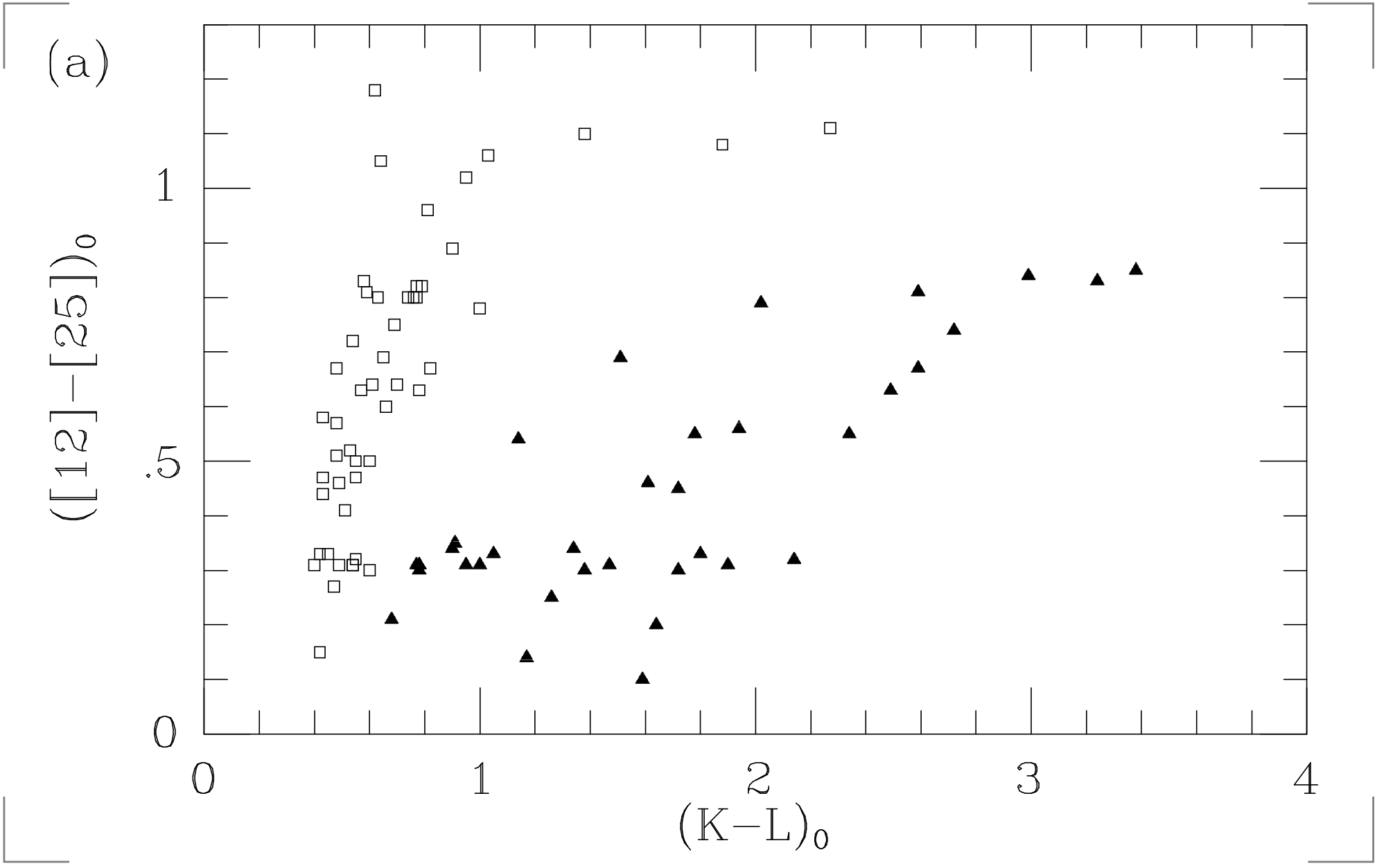
Classification of Oxygen and Carbon Miras

- Using near- and mid-IR two-color diagrams (cf. Epchtein *et al.* (1987)), tentative designations as O-rich or C-rich Miras were determined for 73 Miras with previously unpublished spectral classifications.
- We determined the O-rich and C-rich positions in a $K - L$ versus $[12\,\mu\mathrm{m}] - [25\,\mu\mathrm{m}]$ diagram, the most useful two-color diagram designed to separate Miras.
- The C-rich region is to the bottom right of the diagram, starting at $K - L = 0.65$, while the O-rich region is to the top left.

Classification of Oxygen and Carbon Miras

- The O/C-rich regions here were determined from positions of 11 O-rich and 10 C-rich Miras that had published spectral classifications from the $IRAS$ Low Resolution Spectra (LRS) and other methods.
- The physical reason for this separation lies in the different ratios of near- to mid-infrared opacities for the C-rich and O-rich dust shells around the stars (Le Bertre *et al.* 1994).

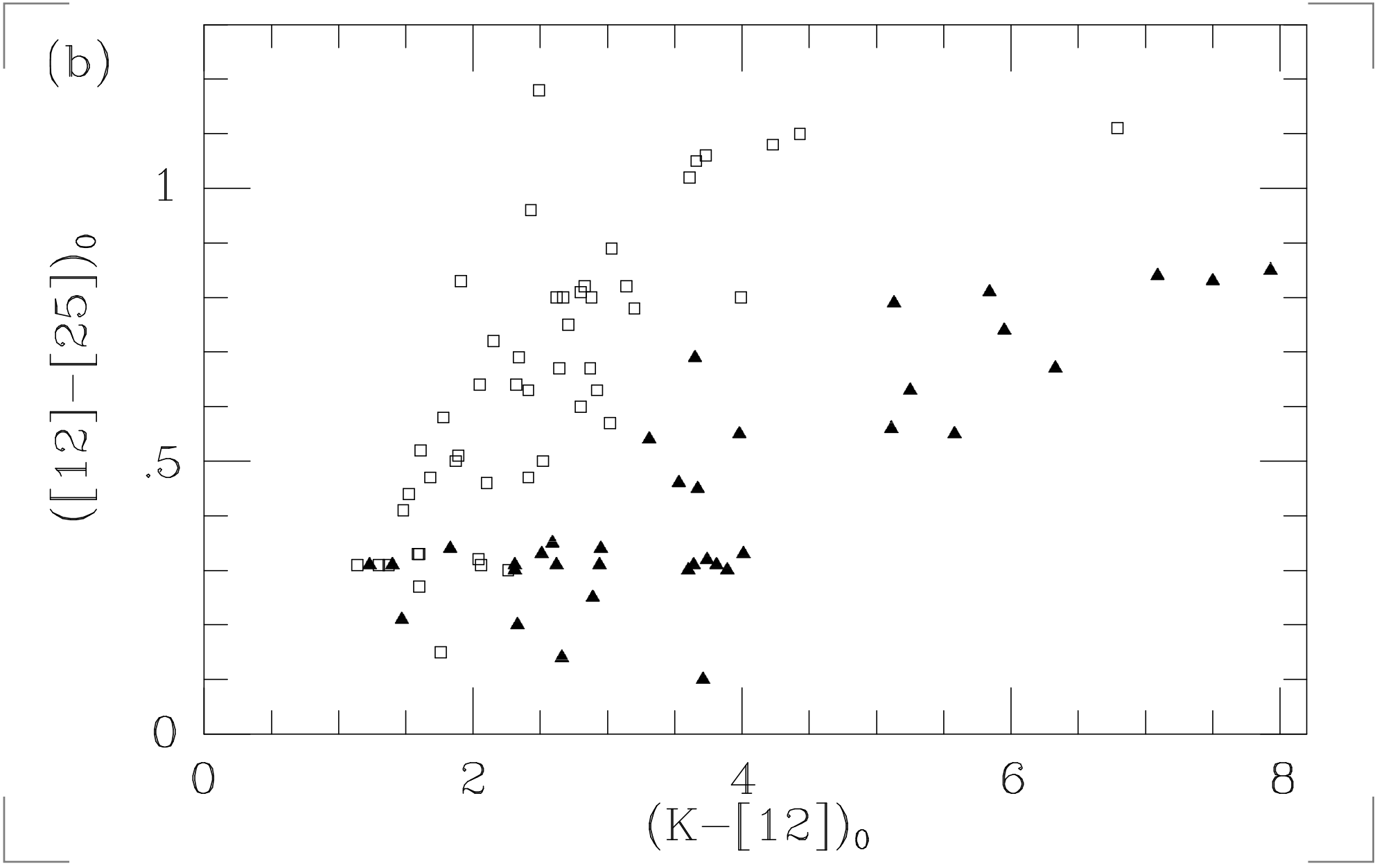
Classification of Oxygen and Carbon Miras



Checking the O-rich and C-rich Discrimination

- O-rich and C-rich, for the most part, falling in different regions on the $K - [12\,\mu\mathrm{m}]$ versus $[12\,\mu\mathrm{m}] - [25\,\mu\mathrm{m}]$ two-color diagram.
- There is however a small region of mixing for Miras with thin shells, i.e. $K - [12\,\mu\mathrm{m}] < 2.2$ mag, low shell temperatures, i.e. $[12\,\mu\mathrm{m}] - [25\,\mu\mathrm{m}] < 0.38$ mag, and with a wide range of periods and amplitudes.
- Therefore, the diagram is seems useful only for checking the classifications from the $K - L$ versus $[12\,\mu\mathrm{m}] - [25\,\mu\mathrm{m}]$ diagram.
- Since the $IRAS$ fluxes are averages of only a few observations for stars that vary in flux, a scatter is expected in the designated O-rich and C-rich locations on these two-color diagrams.

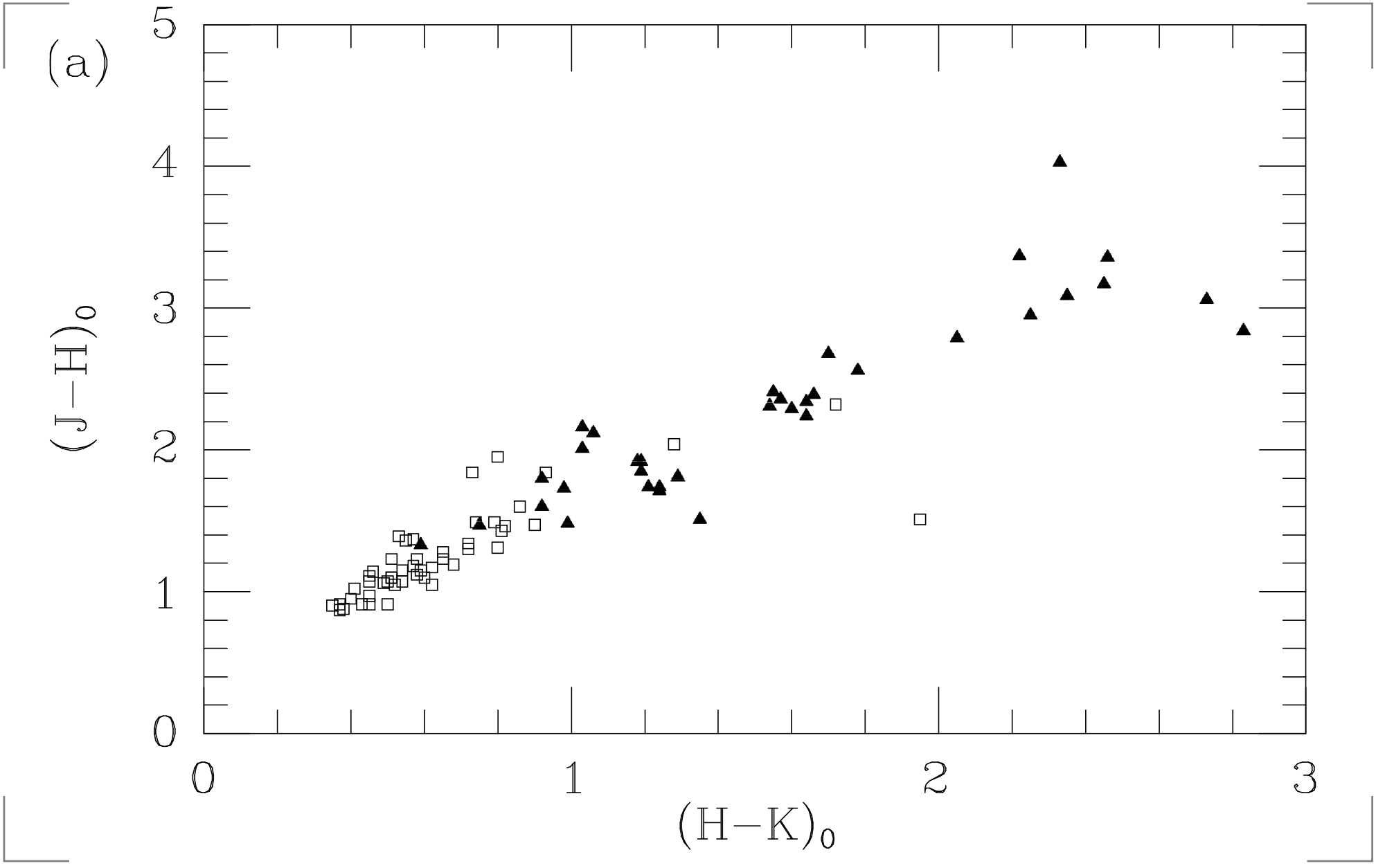
Checking the O-rich and C-rich Discrimination



Near-infrared colors of the O- and C-Rich Miras

- We determined the positions (or colors) of O-rich and C-rich Miras in near-IR two-color diagrams.
- Unlike the near-mid-IR diagrams, near-IR colors alone cannot be used to discriminate O-rich and C-rich Miras.
- In the H versus K diagram, the carbon Miras are redder and all lie above $H - K = 0.9$, but for two stars with exceptionally low amplitudes.
- In the J versus K diagram, the Oxygen Miras are bluer and all below $J - K = 2.9$, but for three stars with long periods: 552, 500, and 1584 days.
- In general, Oxygen Miras in near-IR two-color plots are in a tight blue group, while the Carbon Miras are in a less tight red group, as in similar diagrams by Whitelock *et al.* (1994, 1995) and Whitelock (1996b).

Near-infrared colors of the O- and C-Rich Miras



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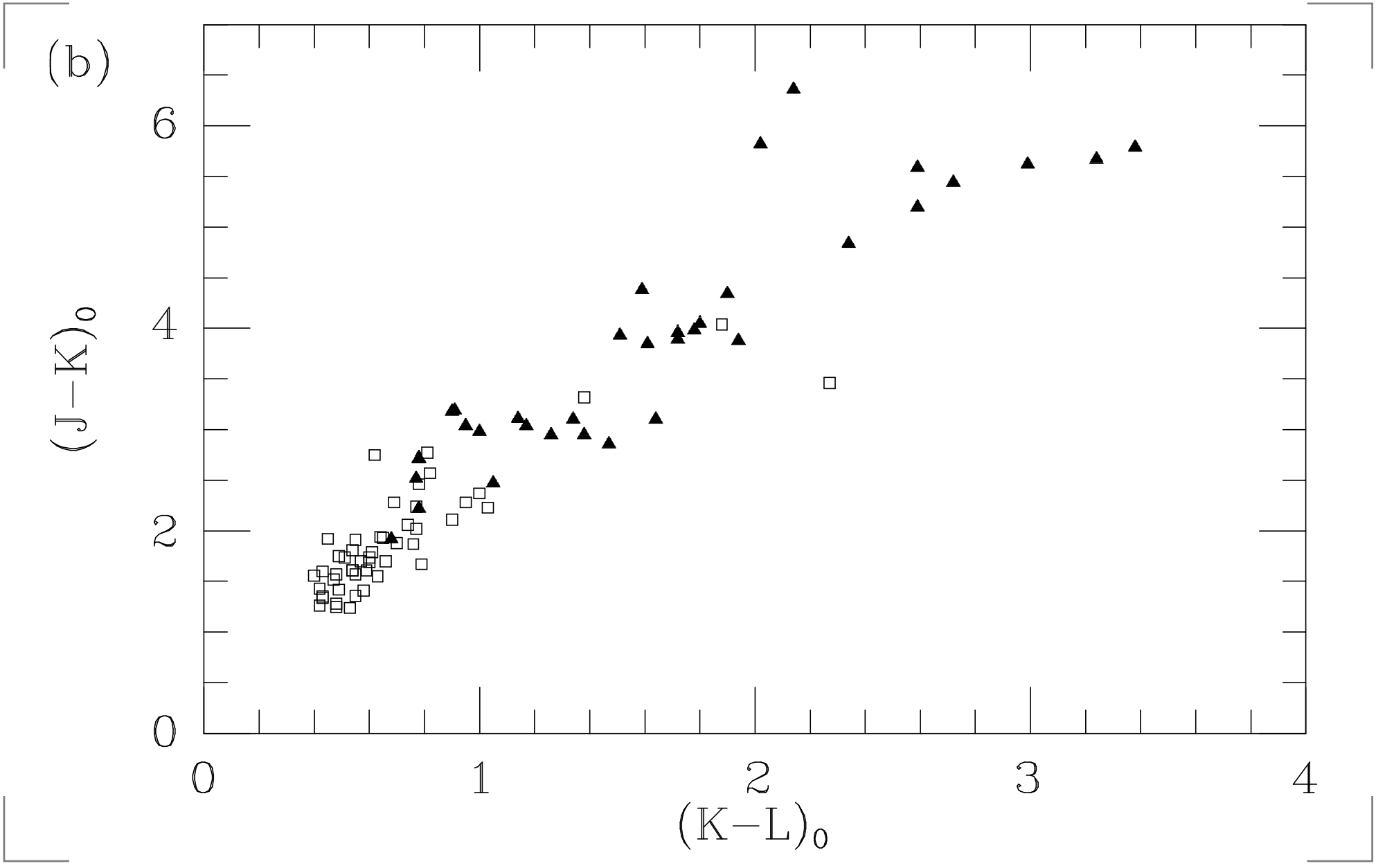
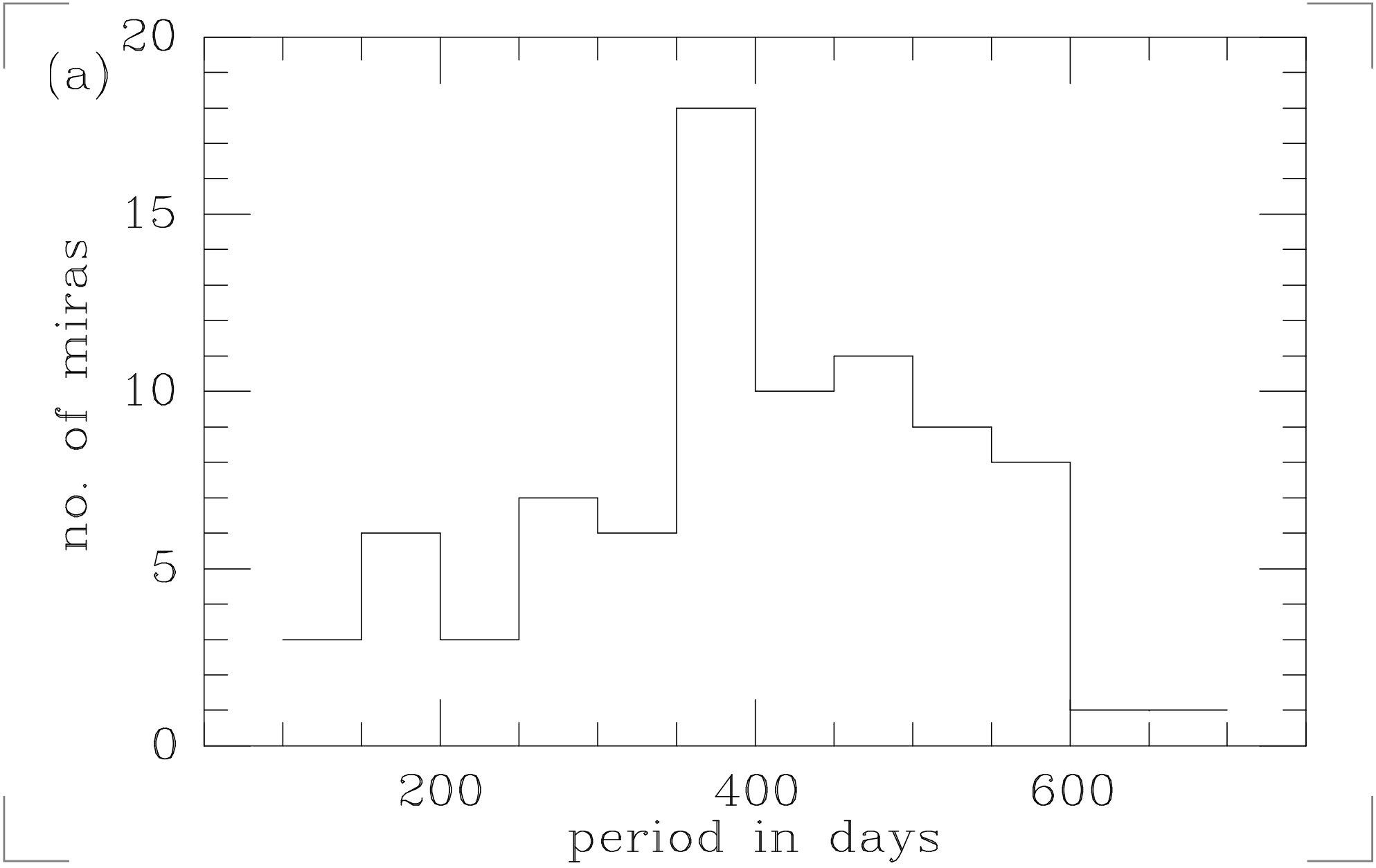


Period Distributions of the O- and C-Rich Miras

- Histograms of numbers of Miras versus period in 50-day intervals were computed.
- Histogram (a) is for both the O- and C-rich Miras, and histogram (b) compares the distribution of the O-rich (dotted-line) and the C-rich (dashed-line) Miras.
- The periods extend from P=100 to P=716 days, with most between P=350 and P=600 days and an average of P=401 days.

Period Distributions of the O- and C-Rich Miras



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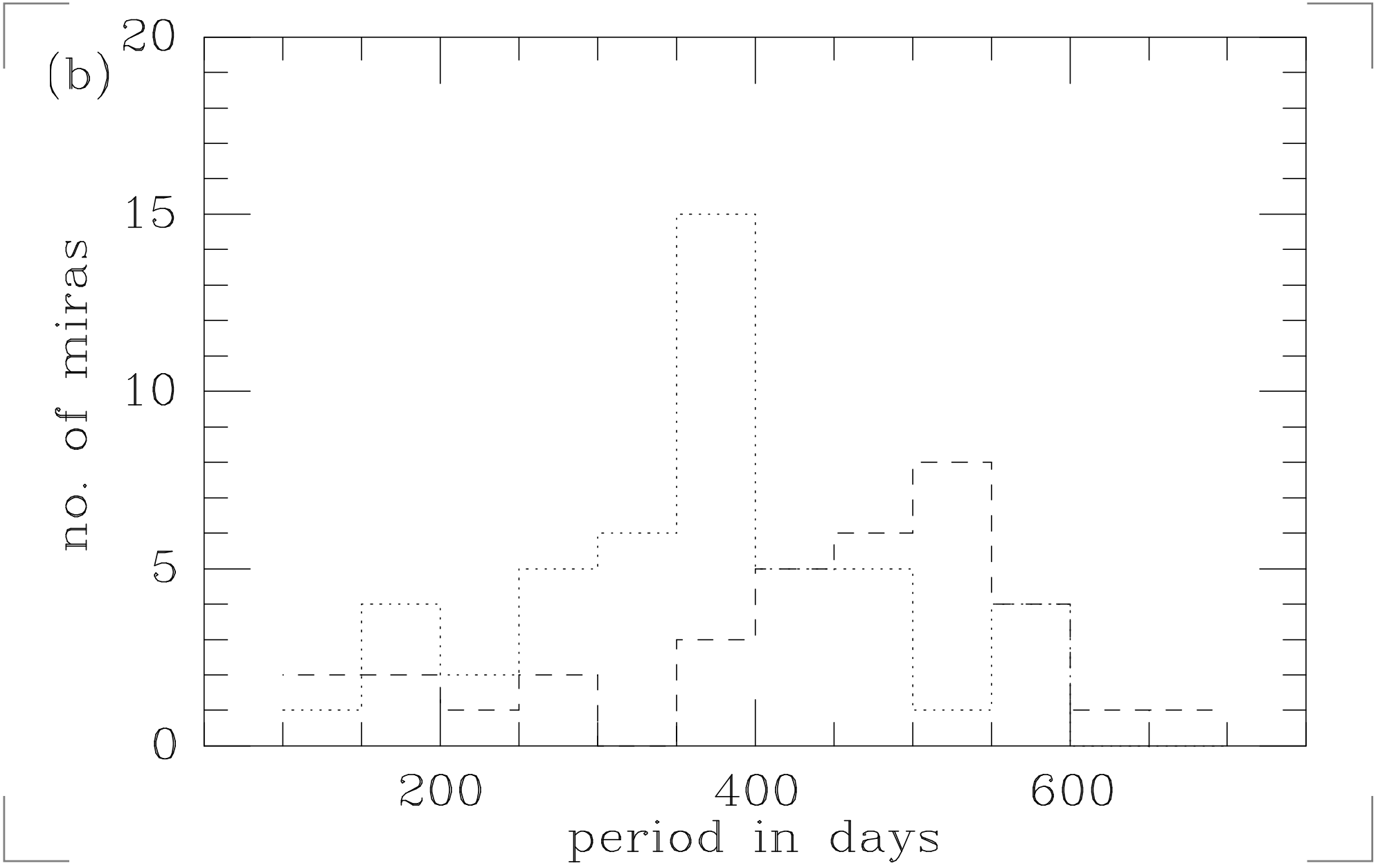


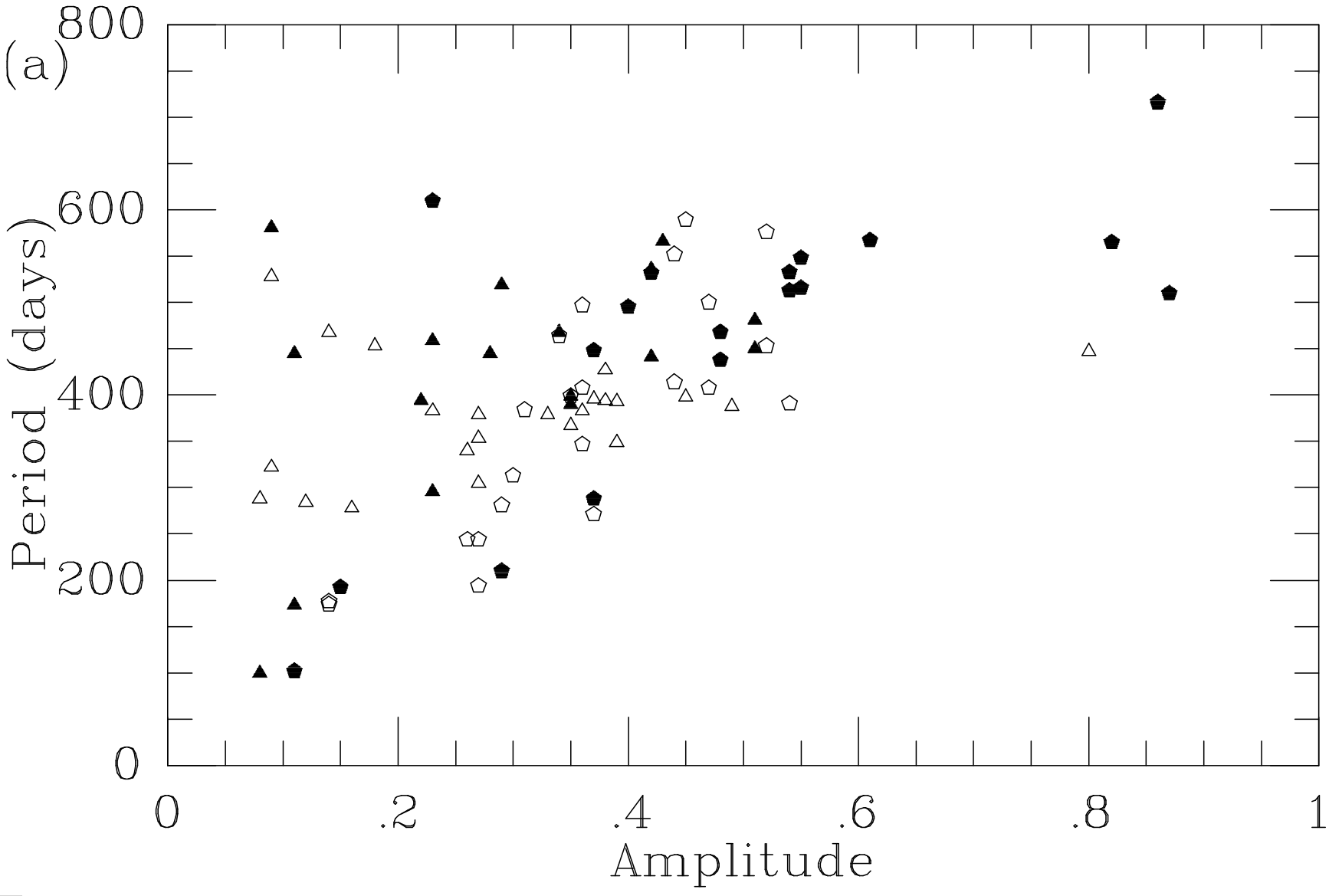
eriod Distributions of the O- versus C-Rich Mira

- The O- and C-rich Miras respectively peak at P=375 days (15 stars) and P=525 days (9 stars), have maximums of P=600 and 525 days and averages of P=386 and 444 days.
- The minimum period for the two types is about the same, just over 100 days.
- According to the Kolmogorov-Smirnov statistical test, there is only a small probability of 0.00055 that the period distributions of the O-rich and C-rich Miras studied here came from the same populations.

Period versus Amplitude for the Mira Groups

- We have obtained a general increase of Mira pulsation period with amplitude, as known for the solar neigborhood and the LMC.
- Here note the large number of C-rich stars with semi-amplitudes > 0.53 mag and the long-period O-rich with semi-amplitudes < 0.2 mag.

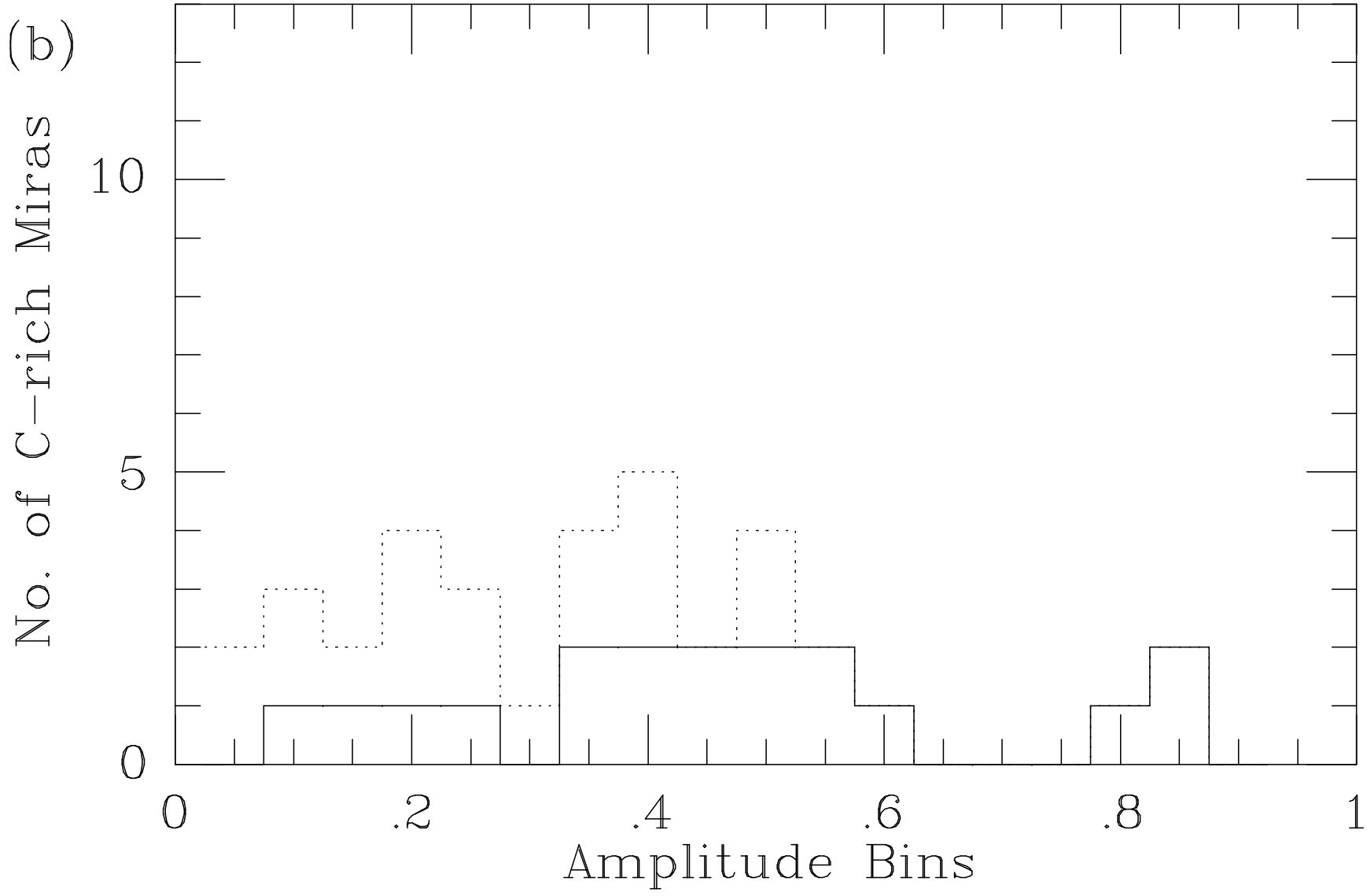
Period versus Amplitude for the Mira Groups



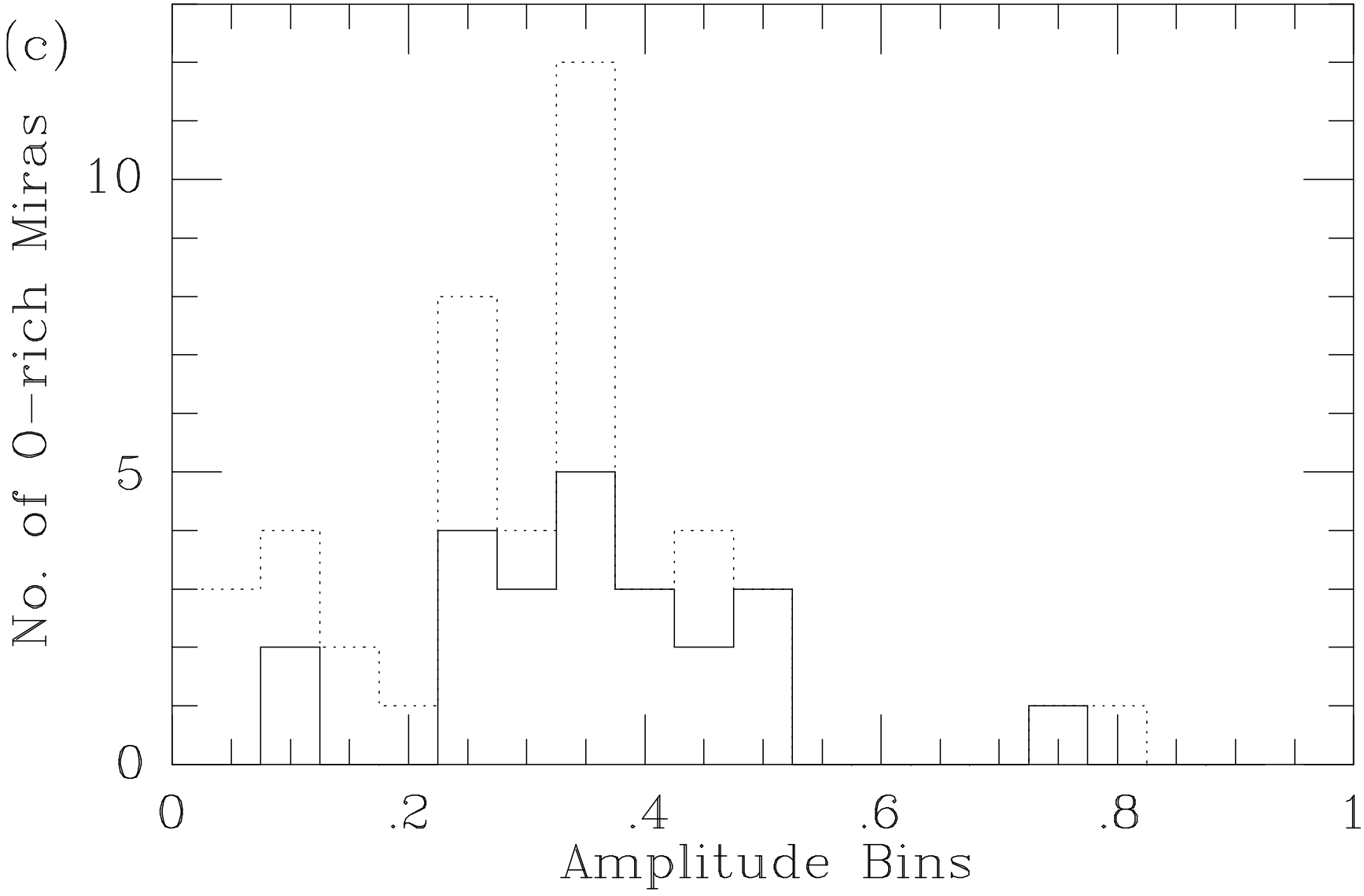
Amplitude Distribution for the Mira Groups

- For Completeness the next histograms [(b) and (c)], respectively, show that the C-rich stars are concentrated between semi-amplitudes of 0.35 and 0.55 mag and the O-rich stars between 0.25 and 0.45 mag.
- In particular, the average semi-amplitudes for the C-rich and O-rich stars are respectively 0.46 and 0.36 mag.
- As this work has shown that Mira amplitude is correlated with period for both O-rich and C-rich Miras and demonstrated that the C-rich Miras have on average longer periods than the O-rich Miras, it is significant and consistent that the C stars have on average also larger amplitudes.

Amplitude Distribution for the C-Rich Miras



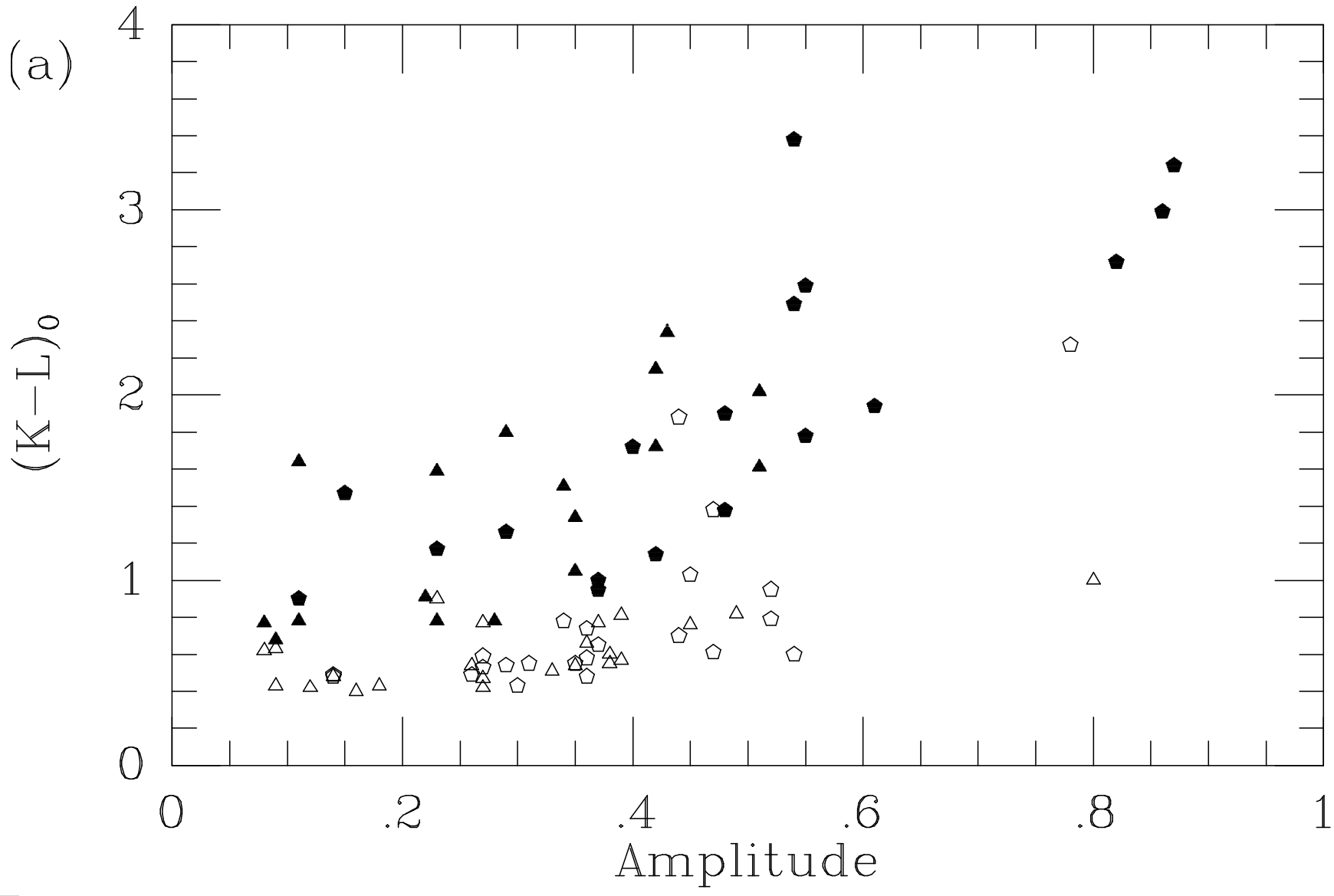
Amplitude Distribution for the O-Rich Miras



Pulsation Amplitude versus Stellar Temperatur

- We investigated the pulsation half-amplitude at K as a function of $K-L$ (stellar temperature), $K-[12\mu m]$ (shell thickness) and $[12\mu m]-[25\mu m]$ (shell temperature).
- For O-rich Miras with thin shells, $K-L$ is a function of stellar temperature.
- However for stars with thick dust shells, $K-L$ is strongly influenced by the reddening of the shell (Whitelock *et al.* 1991), as the O-rich and C-rich shells absorb stellar radiation and influence $K-L$ differently.

ulsation Amplitude versus Stellar Temperatur



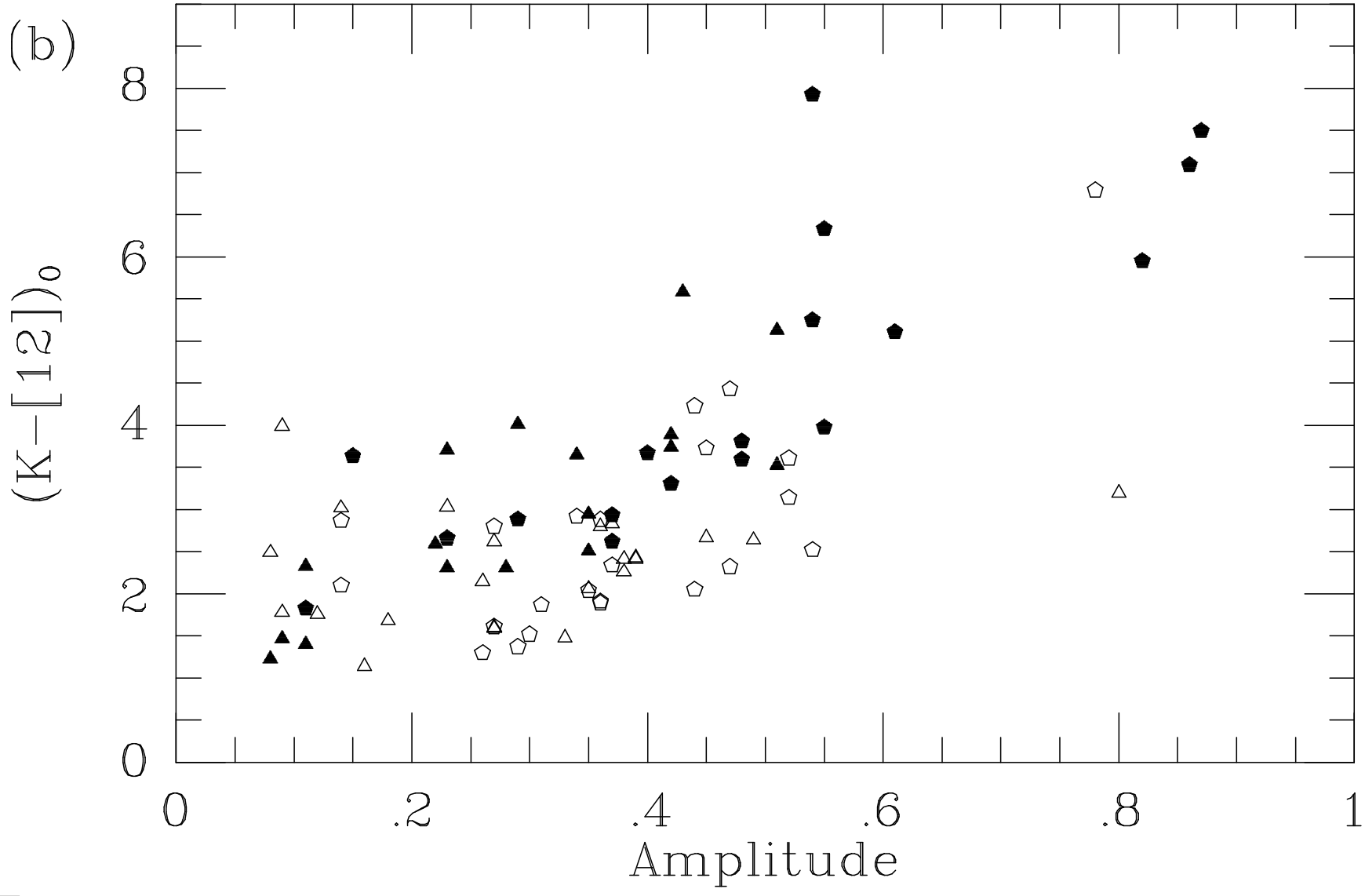
ulsation Amplitude versus Stellar Temperatur

- Separate O-rich and C-rich correlations of $K - L$ with amplitude we obtained indicating that the C-rich stars are generally redder at any given amplitude.
- The correlation for the O-rich stars has a notably smaller scatter.
- It seems the separation of O-rich and C-rich the $K - L$ versus amplitude diagram is primarily because of the $K - L$ color difference of the two groups and not so much because of the difference in the amplitudes of oxygen and carbon stars.

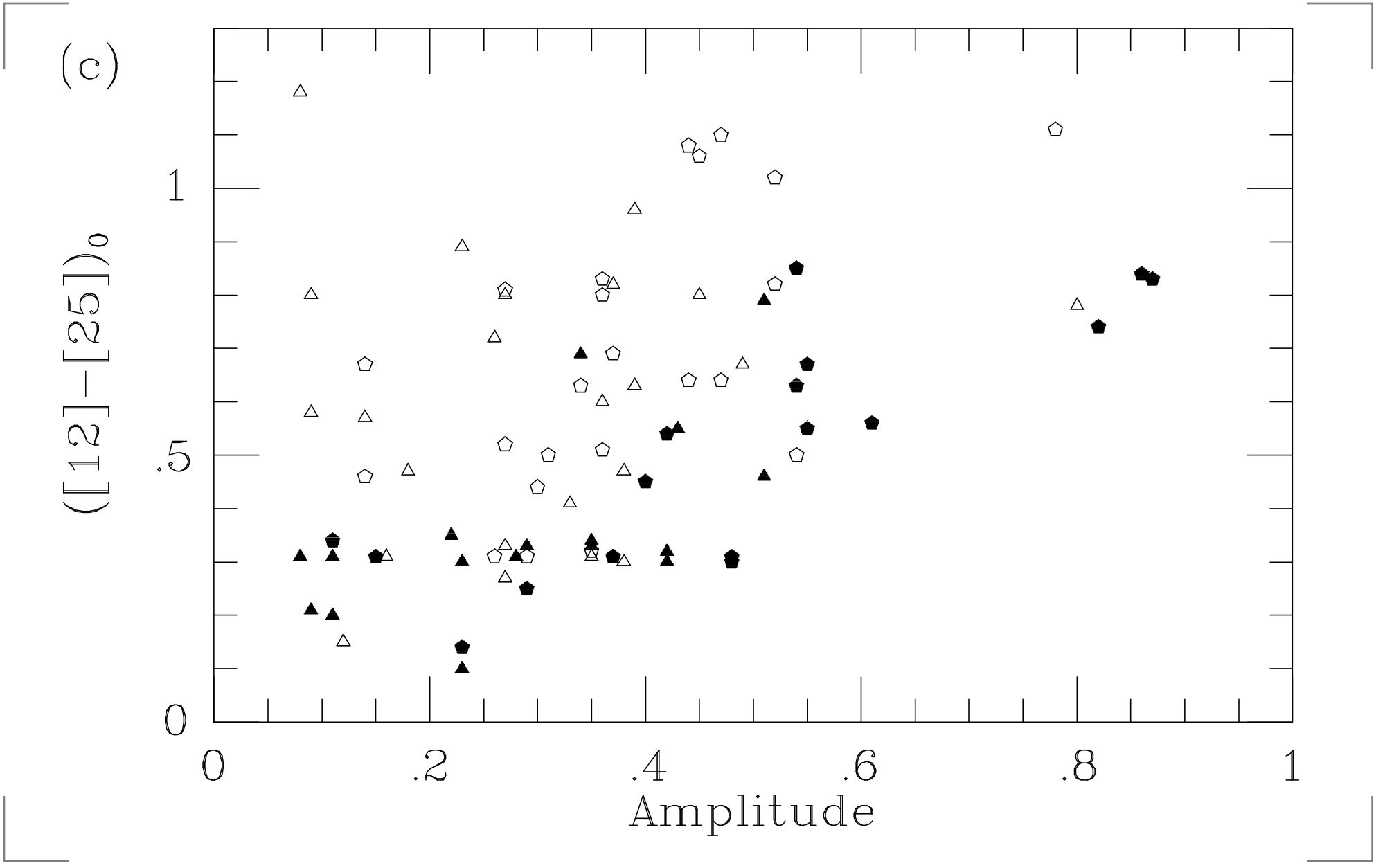
Pulsation Amplitude versus Dust-shell Colors

- There is a correlation of $K - [12\mu m]$ with pulsation-amplitude for both C- and O-rich Miras.
- However, there is a correlation of $[12\mu m] - [25\mu m]$ with amplitude for only the C-rich stars, and no similar correlation for the O-rich stars.
- This may be because the C-rich stars are older and therefore have more evolved dust shells.
- The $K - [12\mu m]$ and $[12\mu m] - [25\mu m]$ correlations show a large scatter, probably because the mid-infrared fluxes are not an average over the full light curve but only over the limited part sampled by $IRAS$.

ulsation Amplitude versus Dust-shell Thickness



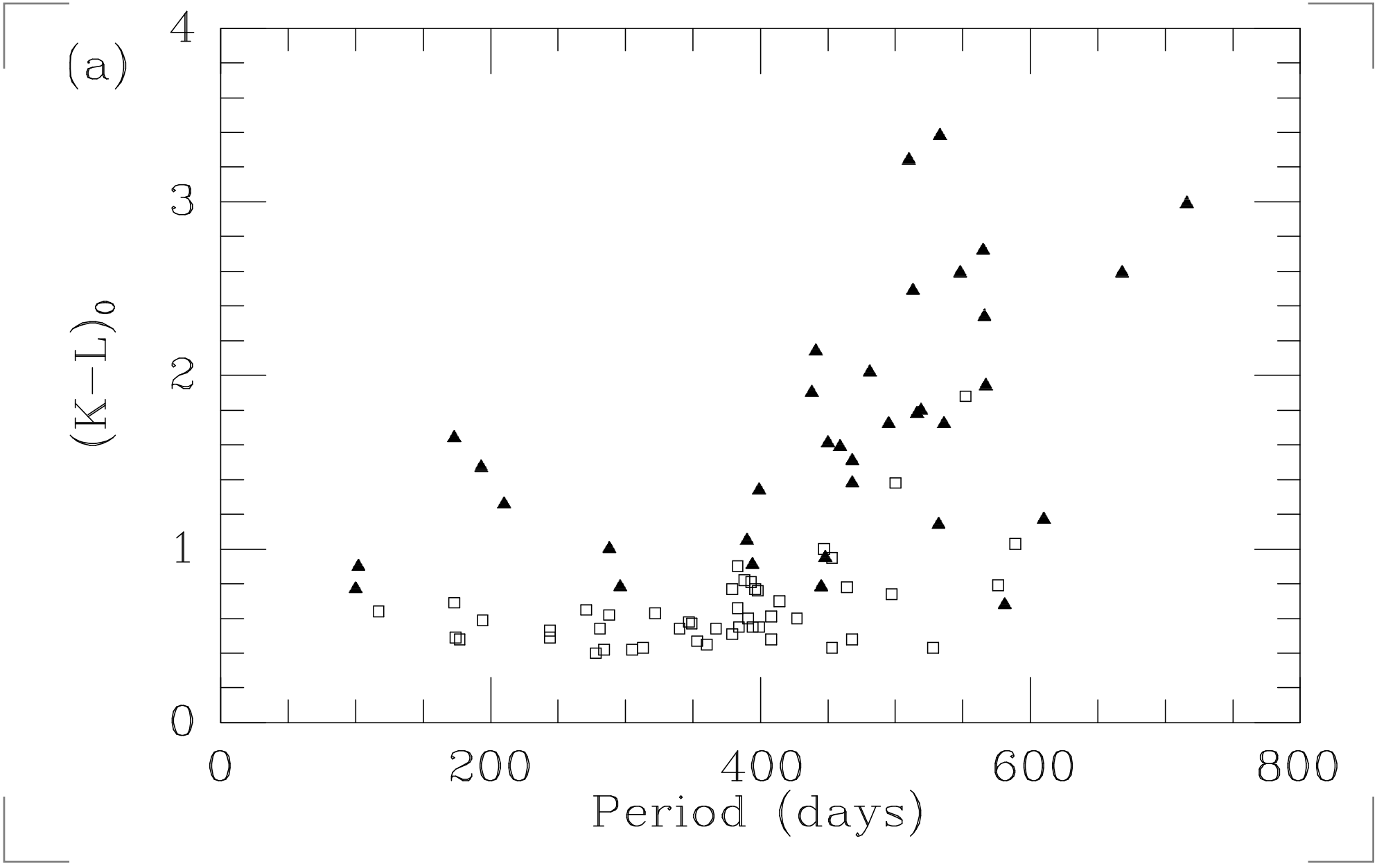
lsation Amplitude versus Envelope Temperatu



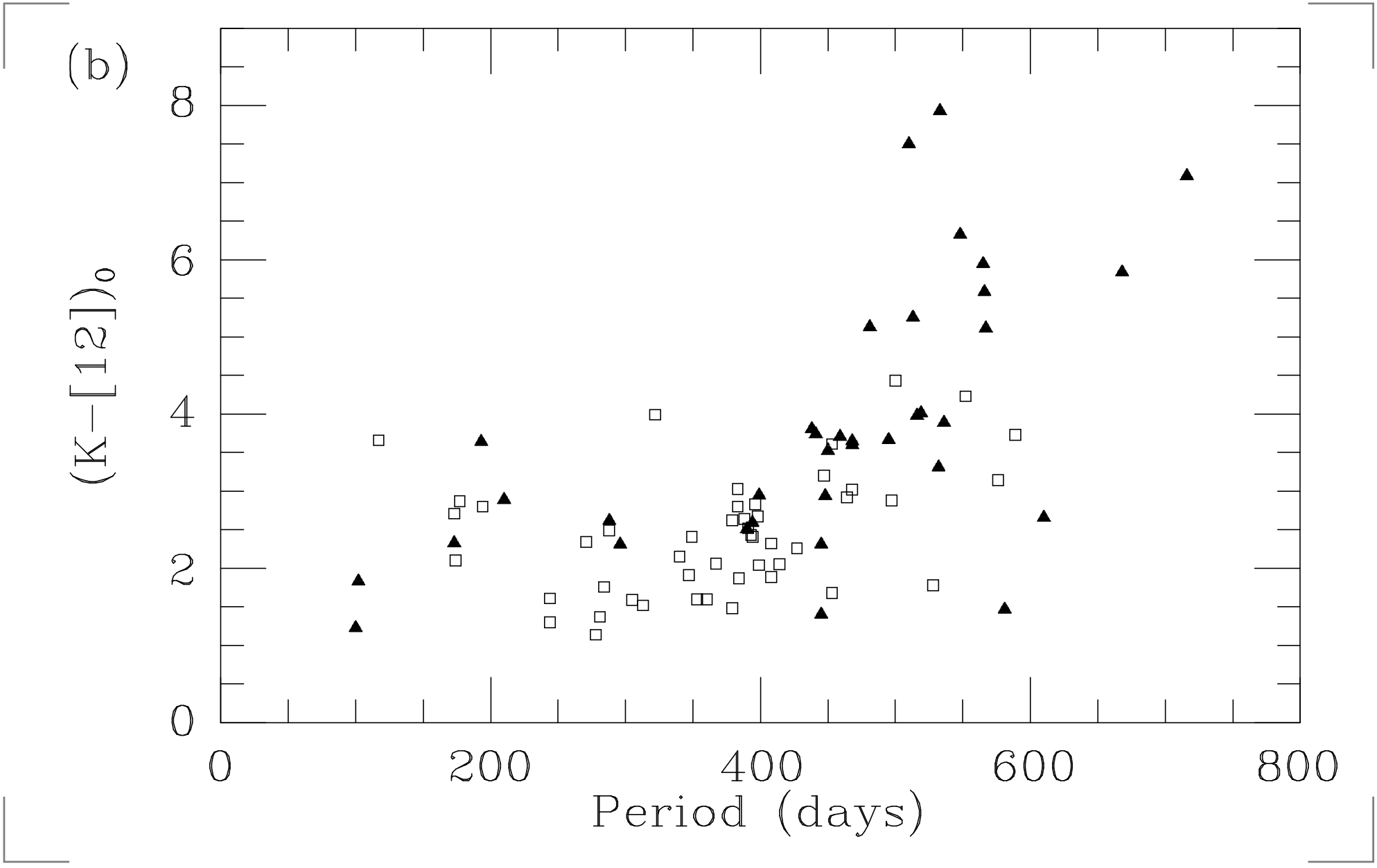
ulsation Period versus Stellar and Shell Colors

- The period as a function of $K-L, K-[12\mu m]$ and $[12\mu m]-[25\mu m]$ colors provide interesting (if not academic) comparisons with the diagrams of amplitude as a function of the same colors.
- The correlations in these figures have different scatters but generally behave alike.
- This is expected as amplitude has been shown to be correlated with period for the Miras for which these quantities are well determined.

Pulsation Period versus Stellar Temperature



Pulsation Period versus Dust-shell Thickness



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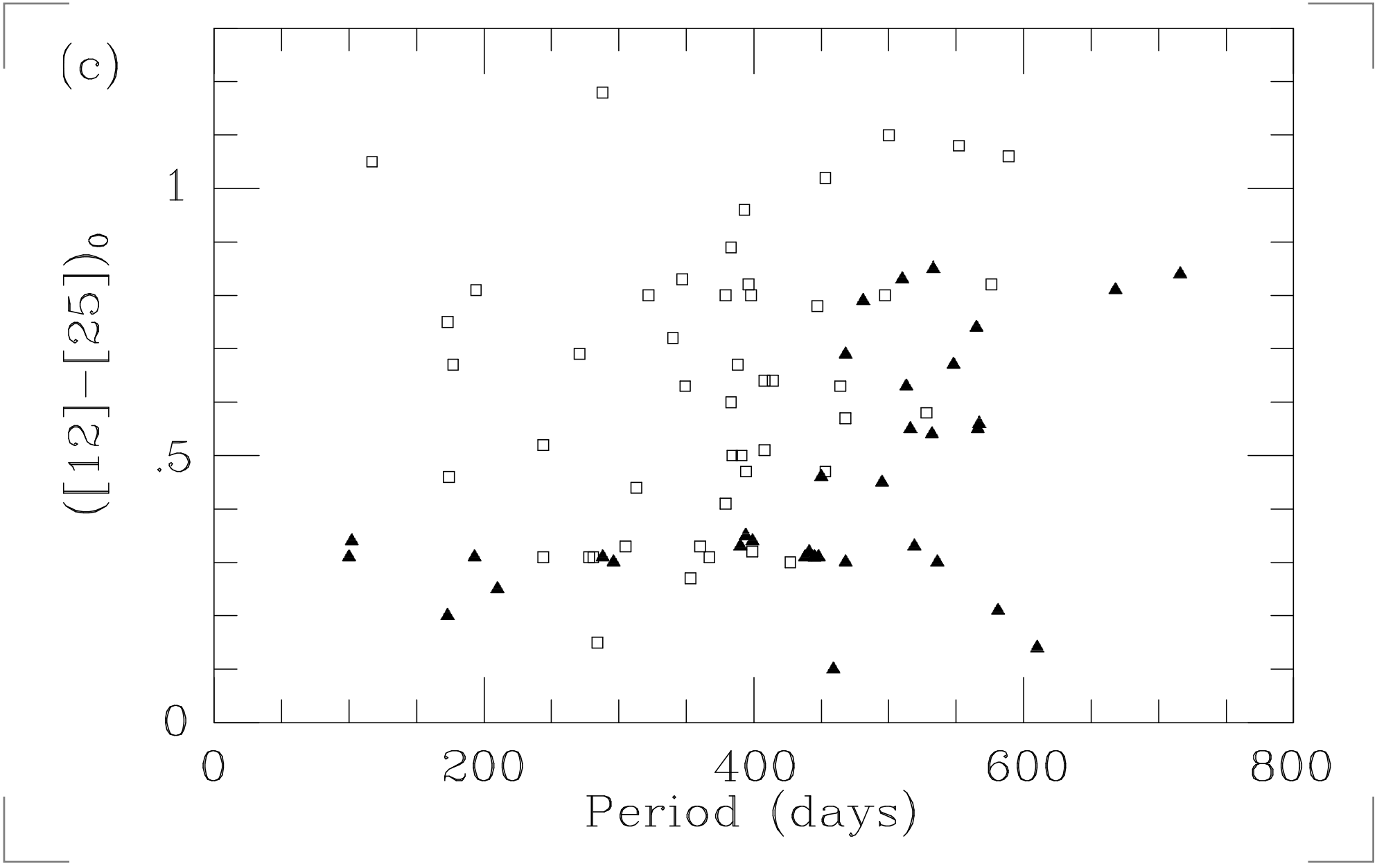

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Acknowledgements

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