Mean light curves of long-period variables and discrimination between carbon- and oxygen-rich stars

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Abstract. Using 75 years of AAVSO data, mean light curve parameters of a sample of 355 long period M, S, and C mira and semi-regular variable stars are investigated. We present a classification of the light curves of LPVs into 6 distinct groups. Combining this classification with IRAS colors makes it possible to distinguish oxygen-rich from carbon-rich miras.[1]

Key words: stars: AGB, post-AGB — methods: data analysis — stars: carbon — stars: variables

1. Introduction

The long-period variables[2] (LPVs) located on the Asymptotic Giant Branch (AGB) represent an important stage of stellar evolution in which some are progenitors of planetary nebula while others are directly evolving to the white dwarf stage (see the reviews by Habing 1990, 1996, and Wood 1990). They play a major part in galactic evolution through enrichment of the interstellar medium in heavy elements via mass loss.

Several investigators (e.g. Whitelock et al. 1991) have studied correlations between observed quantities such as the period and amplitude of light variation, asymmetry of the light-curve shape (rise time expressed as a fraction of the period), the IR excess of the star and its $JHKL$ colours, or parameters derived from the IRAS (*Infrared Astronomical Satellite*) Low Resolution Spectrograph and Point Source Catalog. The period seems to be a particularly important characteristic of LPVs. Campbell (1925) first showed that a statistical relationship exists between the period and the shape of the light curve. The period is also correlated to the infrared excess due to circumstellar dust (De Gioia-Eastwood et al. 1981; Jura 1986), and to the expansion velocity (Ukita 1982; Sivagnanam et al. 1989). These relations could be connected to the link between the period and the estimated mass loss rate (Wood 1990). Whitelock et al. (1986, 1991) have shown that larger mass loss is correlated to longer period and larger amplitude. Furthermore, it has been mentioned in many works that LPVs with more asymmetric light curves lose mass more rapidly than those with symmetric ones (see the review by Jura & Kleinmann 1992a).

As established previously by Feast (1963), and confirmed by many recent works (for example, Feast 1989; Kerschbaum & Hron 1992; Jura & Kleinmann 1992a, 1992b; Jura et al. 1993; Luri et al. 1996), LPVs exhibit distinctive kinematic properties and thus belong to different stellar populations. The period of the star could be a discriminant parameter.

These relationships are still not exactly understood, but it is clear that the period, amplitude, and asymmetry of the light curves of LPVs seem to be closely connected to their pulsation properties and therefore to their evolution. Hence these parameters might be used to define an automatic classification and to identify homogeneous groups of LPVs.

These evolved AGB-stars include three spectral types: M, S, and C, depending on the abundance ratio C/O in their surface layers and on their spectroscopic characteristics. S-stars are probably intermediate objects. A similar dichotomy also exists in their circumstellar material; the silicate and SiC dust features are observed respectively in the oxygen-rich (M-type and possibly S-type) and carbon-rich Miras. This can explain why IRAS colors alone are not sufficient to identify C LPVs. To distinguish

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[1] Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html
[2] The term "long-period variables" is used here to cover Miras and semi-regular variables (according to the definition given in the GCVS, see below). The OH/IR stars are excluded from this study.

carbon- from oxygen-rich stars, Epchtein et al. (1987) propose to use the K- and L-band photometric fluxes.

The purpose of this paper is to study the mean light curve parameters of LPVs, to classify these stars according to these parameters, and to use this classification together with IRAS colors to discriminate between carbon- and oxygen-rich LPVs (Sect. 6).

After a brief description of the data in Sects. 2 and 3, we present in Sect. 4 some statistical results on mean parameters of light curves obtained from the AAVSO visual data over 75 years for a sample of 355 LPVs. In Sect. 5 we present an automatic classification of our LPV sample based on the characteristics of their mean light curve, examine properties of stars belonging to each cluster and the link with previous classifications. Finally, we examine how the IRAS colors and our classification enable us to recognize carbon-rich LPVs.

2. Basic data

The AAVSO has compiled observed times and visual magnitudes for maxima and minima of about 400 LPVs since 1900 (Mattei 1988). Our study is performed on these data which were also used in the preparation of the HIPPARCOS mission. Some stars were excluded from the sample either because of the peculiar shape of their light curves (e.g, double maxima: R Cen, R Nor, RZ Cyg, etc.), or due to insufficient data. The final sample contains 355 stars.

For each star the following parameters of the light curve were derived:

- Period, P: time (in days) from one maximum to the following one.
- Amplitude, A: magnitude difference between the maximum and the minimum.
- Asymmetry factor, f: the ratio of the increasing time (from minimum to the following maximum) to the period.
- Magnitude, Max, at maximum brightness.
- Magnitude, min, at minimum brightness.
- Their respective standard deviations: σ_P, σ_A, σ_f, σ_M, σ_m.

3. Additional data

For each star we have collected the following additional information. Table 1 gives the distribution of the stars according to these additional data.

3.1. Variability type

The General Catalog of Variable Stars (Kholopov et al. 1985, here after GCVS) divides long period red variables into two groups, those with amplitudes greater or less than 2.5 mag. The small-amplitude stars are often called "Semi-Regular" and the larger amplitude ones "Miras". It appears that this amplitude rule is not followed very strictly and that the division between these two groups of LPVs is somewhat artificial (see also Kerschbaum & Hron 1992). However, strong correlation between amplitude and emission features at some specific phase in the visible spectra has been found earlier. Using emission line information, Feast (1972) obtained a similar but not exactly identical division.

3.2. Spectral type

Both Mira and SR variables include M-, S-, and C-type stars. The C/O abundance ratio was the first criterion discriminating the M type (also called oxygen-rich stars, $C/O \lesssim 1$) and the S stars ($C/O \sim 1$), from the C type ($C/O \gtrsim 1$, also called carbon stars). This criterion corresponds to the chemical composition of the surface layers. The second criterion was based on their spectral characteristics (for a review, see Jaschek & Jaschek 1987). Let us remark that the classification of the C stars is less certain than that of M stars, while S stars are the most difficult to classify.

Intermediate objects also exist, as those between S and M stars, called MS and SM stars, or those between C and S stars, called SC and CS. Less common are those between C and M stars, called CM and MC stars (for AGB chemical composition, see Lambert 1988).

3.3. Maser emissions

Masers from late type stars are essentially emitted by three molecules (Elitzur 1980): OH (hydroxyl radical), SiO (silicon monoxide), and H_2O (water). Detection of such maser emission depends both on its intensity and on the distance of the star (Dickinson et al. 1978), thus non-detection of emission can be due either to non-emission by the star or to greater distance of an emitter. Also, the possibility that some stars have asymmetric shells (perhaps because of an asymmetric mass loss) can make detection of maser emission dependent on the star's orientation. Furthermore, in a binary system the companion could supress the maser emissions (Lewis et al. 1987). Despite all this, maser emissions are statistically meaningful.

The pumping mechanism responsible for OH masers is associated with the IR radiation. The properties of type I OH LPVs (characterized by main line emissions) and type II (showing strong satellite emission lines) have been studied earlier and some correlations have been found (Bower & Kerr 1977; Ukita 1982; Sivagnanam et al. 1989), including a strong correlation with mass loss. So, there is some evidence for the following sequence of increasing mass loss rates: (non OH)–(type I OH)– (type II OH)–(OH/IR) stars.

SiO maser emissions seem to be an atmospheric phenomenon (coming probably from the inner regions of the envelope) and thus provide direct information on the

motion in it (Elitzur 1981; McIntosh et al. 1989). Hall et al. (1990) detected changes in the intensity of the SiO masers. Some suggest that the maser luminosity may depend strongly on the mass loss rate (cf. Bowers 1985).

The H_2O maser emissions are still the less-studied ones; the difficulties come from the strong variability of their profiles (e.g. Bowers et al. 1993). Even so, a relationship has been suggested between these variations and the mass loss rate (Engels & Lewis 1990; Bowers & Johnston 1994).

4. Parameters of the light curves

4.1. Mean parameters

Mean parameters have been calculated for the light curve of each star of our sample using 75 years of AAVSO data. Their average values and standard deviations are given in Table 2. The information in the columns is as follows:

- *Column (1):* The name of the star.
- *Columns (2) to (5):* The available number of entries for the periods, maxima, minima, and visual amplitudes, respectively.
- *Column (6):* The mean period.
- *Column (7):* The mean asymmetry factor.
- *Column (8):* The mean magnitude at maximum brightness.
- *Column (9):* The mean magnitude at minimum brightness. We note that the average magnitude at minimum for some stars may have low reliability due to the observationnal limit that can be reached at this phase. The minima of these stars should be treated with caution; the standard deviations can give a confidence level.
- *Column (10):* The mean visual amplitude. On average, the estimation of the amplitude from either maximum to the following minimum or else from minimum to the following maximum, lead to the same value. Note, however, that low reliability of the minima causes a low confidence of the corresponding amplitude value. Hence, some mean amplitudes should be treated with caution.
- *Columns (11) to (15):* The standard deviations of, respectively, period, asymmetry factor, magnitudes at maximum and minimum, and amplitude.
- *Columns (16) to (17).* Variability type and spectral type taken from the GCVS.

4.2. Properties of some standard deviations

Figure 1 shows that, except the semiregular variables of M spectral type, the other LPVs roughly obey $\sigma_P \sim$ constant for $P \lesssim 275$ days and a relation $\sigma_P/P \sim$ constant for longer periods. This could be related to the fact that longer-period stars generally exhibit more complex pulsation, inducing more important mass-loss.
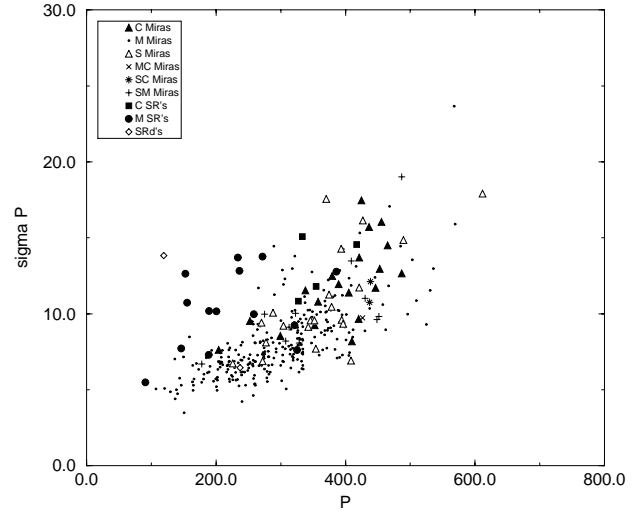
Fig. 1. The standard deviation of the period as a function of the period length for the 355 LPVs. Dots are for M Miras, triangles for S Miras, filled triangles for C Miras, cross for MC Miras, asterisks for CS or SC Miras, plus for SM or MS Miras, filled circles for M SRa's or SRb's, filled squares for C SR's, diamonds for SRd's

4.3. Period-amplitude-asymmetry relations

Reviews about the importance of these parameters are given by Whitelock et al. (1991) and by Jura & Kleinmann (1992a). We have summarized our results in Fig. 2. We distinguish between Miras and SRs, and the various spectral types.

As is well-known, we find in general that carbon-rich Miras have large periods with small amplitudes, and that only a third of them show significant asymmetry in their light curves. S-Miras have large periods and amplitudes. Only S-Miras show a clear tendency of increasing amplitude with period. The "continuity" between SR's and C-stars is to be noted.

5. Automatic classification

We have attempted to classify the 355 LPVs based on three parameters characterizing their mean light curves: period P, amplitude A, and asymmetry factor f. Mennessier (1985) realized such classification on a smaller sample covering a shorter time span of observations. Ludendorff (1928) made an earlier classification of LPVs based on the shape of their visual light curves (see also Mattei 1983).

We used a dynamical clustering, which is a non-hierarchical analysis (Murtagh & Heck 1987), and point out that the optimum number of clusters from the

Table 1. Summary statistics

		Variable type		Spectral type			OH emission			SiO emission			H$_2$O emission		
		Mira	SR	M	S	C	Y	N	?	Y	N	?	Y	N	?
Variable type	Mira	335													
	SR	–	20												
Spectral type	M	286	14	300											
	S	27	0	–	27										
	C	19	4	–	–	23									
OH maser emission	Y	52	0	52	0	0	52								
	N	171	6	172	2	2	–	177							
	?	111	14	76	25	20	–	–	125						
SiO maser emission	Y	94	1	89	5	1	44	41	10	95					
	N	108	5	107	5	1	7	98	8	–	113				
	?	133	14	104	17	21	2	38	107	–	–	147			
H$_2$O maser emission	Y	69	2	71	0	0	36	32	3	51	15	5	71		
	N	168	9	147	20	9	13	109	55	41	69	67	–	177	
	?	98	9	82	7	14	4	36	67	3	29	75	–	–	107

inertia criterion seems to be six. From several random initial conditions the best partition was extracted.

Each cluster of the best partition is characterized by its position in (P, A, f)-space as given in Table 3. It turns out that P and A are independent parameters in this classification, but that f appears in linear combinations with P and A. The classification is realized in terms of the four variables P, A, $100f - 5.9A$, and $100f - 0.0022P$, which are discriminant parameters, and are easily determined from observations.

5.1. Properties of stars in each cluster

5.1.1. Spectral types

The number of stars of each cluster according to their spectral type is given in Table 4. It is notable that 80% of C stars belong to cluster C3. Still, this cluster also contains M stars, so this classification is not sufficient to discriminate C-rich from O-rich LPVs. Note the similarity between clusters C2 and C4 (in which there are no carbon stars), as well as that between C3 and C5 (which contain most of the C stars and SRs respectively).

5.1.2. Maser emission

The contingency table of maser emissions and our clustering is given in Table 5. In each column the number of stars is indicated, followed (in parentheses) by 100 times the ratio of the observed frequency to that which is expected if the variables are independent:

$$p_{ij} = 100n_{ij}/f_{ij} = 100(n_{ij}/n_{i.}n_{.j})n, \tag{1}$$

where n is the total number of individuals, $n_{i.}$ the total number in line i and $n_{.j}$ the total in column j. Significantly high and low ratios are indicated by one or two underlines respectively.

As can be predicted, maser emission has not been searched for among C stars. The significant frequencies confirm that:

1. OH emission is related to longer period and asymmetric light-curves (C1 and C6) and not to short-period variables (C2 and C5).
2. SiO emission is related to longer period and large amplitude (C6 and C4) and not with short periods (C2 and C5).

Table 3. The characteristics of the six best clusters as achieved from an automatic classification (dynamical clustering), n is the number of stars belonging to each cluster

Best cluster	n	P	A	$100f-5.9A$	$100f-0.022P$
C2	110	$< \sim 275$	> 3.7	> 10.5 & < 26	$-$
C4	67	$> \sim 275$	> 3.7	> 10.5 & < 26	> 35
C1	54	$> \sim 275$	< 4.7	> 10.5 & < 26	< 35
C6	51	$> \sim 275$	> 4.7	< 10.5	< 35
C5	37	$< \sim 275$	< 3.7	> 26	$-$
C3	35	$> \sim 275$	< 3.7	> 26	> 35

Table 4. Number of stars in each cluster according to different types

Type	C1	C2	C3	C4	C5	C6
O rich						
Miras	48	106	12	59	25	40
SRs	1		3		12	
C rich						
Miras	4		15		1	1
SRs			4			
S	1	4	1	8		10

Table 5. Contingency table of our classification and maser emissions. Y and N respectively signify a "yes" or "no" to maser detection

	OH emission						SiO emission						Tot. by line
	Y		N		?		Y		N		?		
C3	3	(57)	12	(69)	20	(162)	7	(75)	3	(27)	25	(172)	35
C5	1	(17)	25	(132)	12	(90)	0	(0)	15	(124)	23	(146)	38
C4	10	(100)	38	(114)	19	(81)	26	(145)	17	(80)	24	(87)	67
C2	3	(18)	76	(139)	31	(80)	15	(51)	58	(166)	37	(81)	110
C1	14	(174)	14	(52)	26	(137)	14	(97)	13	(76)	27	(12)1	54
C6	22	(289)	12	(47)	17	(95)	33	(242)	7	(43)	11	(52)	51
Tot. by column	53		177		125		95		113		147		Тот. 355
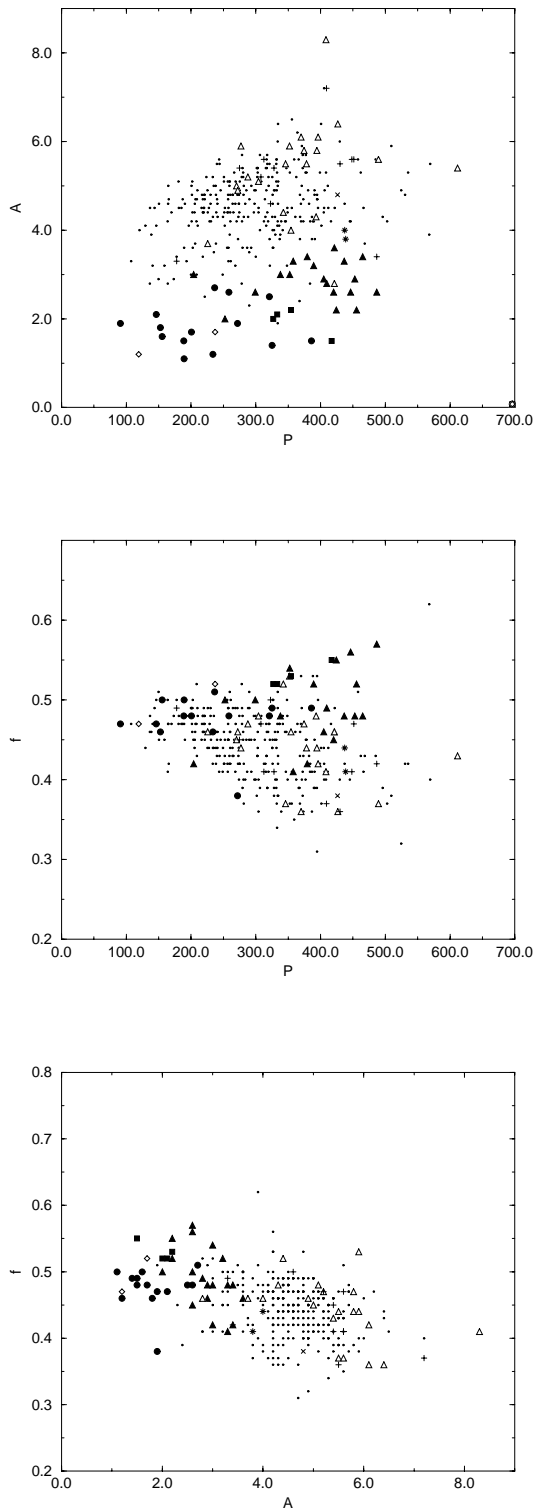
5.1.3. Other classifications

Automatic classifications using the dispersions σ_M, σ_m, σ_A were performed by Brito et al. (1992). The aim of this paper was to check a method of symbolic clustering by comparing it to a classical method. Their results led to a six-cluster classification; the contingency table with ours is given in Table 6 (the numbers have the same meaning as in Table 5). We conclude that:

1. S2 and S6, whose members are characterized by small or mean values of the three dispersions, are related to C3 and C5. This agrees with known properties of SR and C stars.
2. Mean or high values of dispersions (S4, S1, S5, S3) are mainly associated with clusters C1 and C6, which contain the most asymmetric light-curves.

6. IRAS colors and light-curve clustering

As we have emphasized, the difference between carbon- and oxygen-rich stars depends on several parameters (the abundance of specific elements, the evolutionary state of the star, its chemical composition, its mass, etc.) to which the pulsation and the light curve are related. We have just seen that the light curve parameters are not sufficient to distinguish C stars. These parameters are mainly linked to the stellar rather than circumstellar properties. The properties of their circumstellar envelopes differ, but it is well known that parameters linked principally to the circumstellar medium, such as IRAS colors, also are not sufficient to distinguish C stars. Yet it may be that the combination of both sets of parameters, respectively reflecting the stellar and circumstellar properties, could be used to distinguish carbon- from oxygen-rich LPVs. Therefore we now look jointly at light curve parameters and IRAS colors.
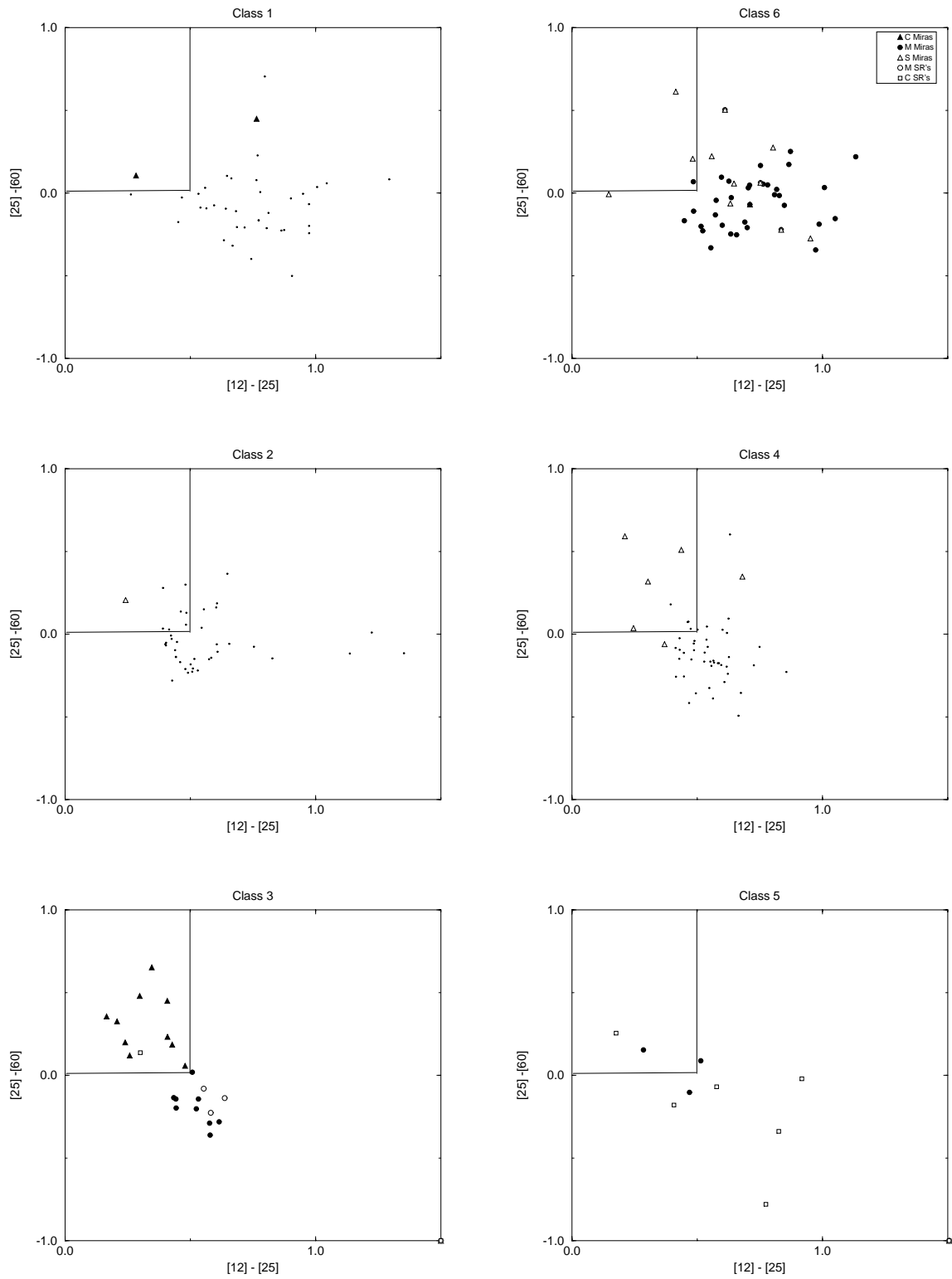
6.1. Our sample

Figure 3 shows the classical $([12] - [25], [25] - [60])$ IRAS color-color diagram separately for each cluster found by our light-curve classification. Only IRAS fluxes with a good quality (3) are considered. It can be seen that:

1. non-C miras belonging to C3 have IRAS colors different from the C miras belonging to C3,
2. non-C miras with IRAS colors in the range of the C miras belong to clusters other than C3.

This indicates that by considering both IRAS colors and light-curve classification, we can discriminate C-rich from O-rich LPVs.

6.2. GCVS sample

We have now to check if this result is robust or only due to a peculiarity of our sample. So we selected all miras in the GCVS with IRAS colors of quality 3. To generate this

Fig. 2. Amplitude-period-asymmetry relations for the 355 LPVs discriminating by variability and spectral types. The symbols are the same as in Fig. 1

Fig. 3. IRAS color-color diagram for each cluster

Table 6. Contingency table of our classification and the one obtained from the dispersions of light curve parameters

	S4		S1		S2		S6		S5		S3		Tot. by line
C3	4	(59)	4	(52)	15	(<u>188</u>)	7	(91)	3	(132)	2	(78)	35
C5	1	(<u>13</u>)	7	(84)	12	(138)	17	(<u>204</u>)	0	(<u>0</u>)	1	(<u>36</u>)	38
C4	15	(115)	11	(75)	21	(137)	12	(81)	2	(46)	6	(122)	67
C2	18	(84)	29	(120)	27	(108)	32	(132)	0	(<u>0</u>)	4	(50)	110
C1	9	(86)	19	(<u>160</u>)	2	(<u>16</u>)	7	(59)	10	(<u>286</u>)	7	(<u>177</u>)	54
C6	22	(<u>222</u>)	8	(71)	4	(<u>34</u>)	3	(<u>27</u>)	8	(<u>242</u>)	6	(<u>161</u>)	51
Tot. by column	69		78		81		78		23		26		Tot. 355
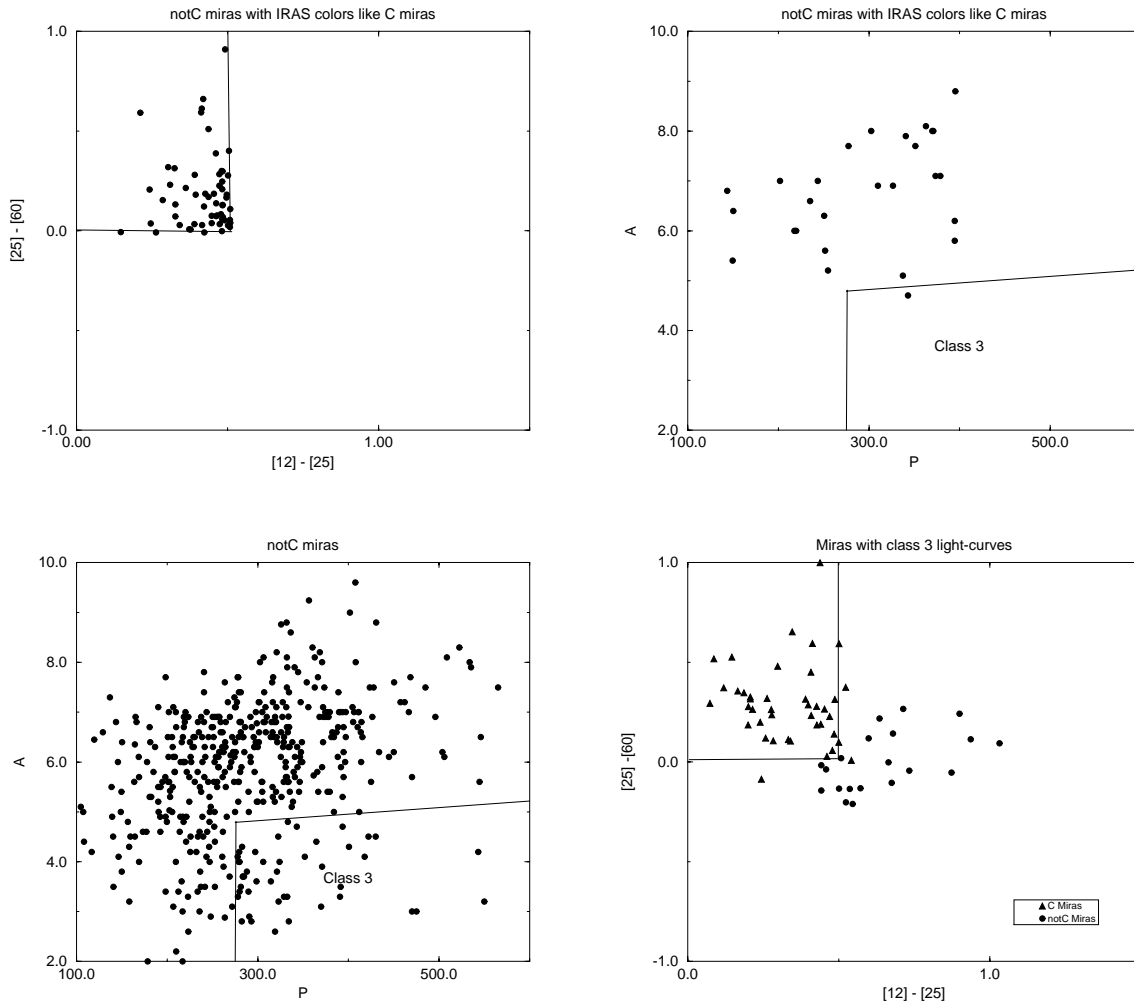
Fig. 4. IRAS color-color diagram and location on (P, A) plane for different samples

sample we used the database ASTRID (Mennessier et al. 1996).

The results are displayed in Fig. 4. It must be noted that to compute the amplitude, we must compensate for the fact that the GCVS indicates not the *mean* maxima and minima, but the most luminous and the least luminous observed magnitudes. To define the corresponding limits of C3, we must apply statistical corrections (Mennessier & Guibert 1983) to the GCVS data:

$$\max_{\text{mean}} = \max_{\text{GCVS}} +0.32 + 0.11(P/100), \tag{2}$$

and

$$\min_{\text{mean}} = \min_{\text{GCVS}} -0.6. \tag{3}$$

We confirm that:

1. miras of S and M spectral types with IRAS colors like the ones of carbon miras do not belong to C3
2. non-C miras belonging to C3 have IRAS colors different from C miras belonging to this cluster.

Hence we verify our previous conclusion: combining IRAS colors with our classification enables us to distinguish carbon-rich from oxygen-rich miras.

7. Discussion and outlook

This paper is based on a statistical study of observations over an exceptionaly long period of time. We confirm previously known results that can help explain many other observational data and constrain the models.

Our main result is to produce a classification of LPVs from relatively easily observable parameters of their light curves that can be used jointly with IRAS colors to distinguish carbon- from oxygen-rich stars. One of its strengths is that all parts of these stars (stellar and circumstellar media, extended envelope, and their couplings) are taken into account.

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