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"Inter-Longitude Astronomy" project: long period variable stars

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This article contains the highlights of complex studies of long-period variable stars such as Miras: semiregular, symbiotic (particularly, pulsating symbiotic), as well as RV Tauri-type stars. In the course of these studies, important characteristics of mean light curves were determined. In the case of multi-component variability, additional periods were found. Correlations between parameters of mean light curves were investigated. The cycle-to-cycle changes of light curve parameters were analysed using various mathematical methods. Classification criteria of variable stars and effects of variability were proposed based on this research. The study of observational parameters and the correlations between them can be used to estimate the age, mass, and other physical characteristics of AGB stars.

Key words: AGB and post-AGB, (stars:) binaries: symbiotic; stars: oscillations (including pulsations); stars: variables: general

INTRODUCTION

Studies of long-period variable stars (LPV), as well as their evolutionary status and pulsating activity, represent a special interest. These types of stars are located in the large luminosity and low temperature region of the H-R diagram. Mira-type stars are the most numerous. The stars of semiregular types of variability and OH/IR stars (mainly SR-supergiants) adjoin directly to them. All these objects — asymptotic giant branch (AGB) stars — are intrinsically related to one another, and are at different stages of their evolution towards the most probable final stage of a planetary nebula. Three kinds of circumstellar maser, discovered from a large number of AGB-stars, exhibit a particular variation of radiation related to own rotation. Mira-type stars are studied practically at all wavelength ranges. This concerns especially near and far IR-regions. Observations in the visible spectrum are mainly carried out by astronomy amateurs.

It is challenging to obtain the light curve of a Mira-type star because the periods of pulsations are close to one year and the amplitude is large ($5-10^m$). Spectral observations are complicated because of the presence of molecular bands. However, the total visual light curve is sufficient to help form a first opinion on the star, to classify it and to derive a further program of its study. At present, several problems are associated with the study of the Mira-type stars and (close to them) semiregular stars. The general problem is to determine the mass.

The majority of Miras are known as single stars. There are several Mira-type stars in symbiotic systems (o Cet, UV Aur, RR Tel, R Aqr), and the binarity of others is suspected (R Aql, U Her). Masses of Mira-type stars cannot be determined directly from pulsating theory, since the duration of the pulsating period varies with time. The radial velocities undergo a jump, making it impossible to determine the radius. It is also problematic to use the "period – luminosity" relation usually applied for cepheids, because of the distance uncertainty. So the study of the observational parameters, which could be used to estimate masses and ages of the Mira-type stars, is of a significant interest. Besides the period of the brightness variations, the IR-luminosity and maser's fluxes can be used as fundamental characteristics of a Mira-type star, and these values can be obtained from observations. All of these parameters are correlated among themselves, as well as with the visual brightness of the star. Perhaps we have a chance to use these common parameters to divide the Mira-type stars into two groups: the stars that directly evolve to white dwarfs, and the stars that pass the

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stage of planetary nebulae. Particularly the latter stars are formed via intensive mass loss at the AGB-stage.

From studies of the kinematic characteristics it is known that the Mira-type stars with periods $P < 250^d$ and $P > 250^d$ belong to different stellar populations and have different initial masses [17]. Our investigations consider the inter-dependencies of all photometrical parameters of the light curves of Mira-type stars (not only the value of the period, which changes during the Mira-type stage). This makes it possible to distinguish the stars into groups according to the complete set of properties, to estimate their evolutionary stage relative to one another, and using the light curves, to mark the groups with different initial masses [22].

Moreover, the shape of the light curve can give information on the mode of stellar pulsations, if, for example, it is used in conjunction with the colour index curves, as is proposed by Dawson & Baird [16], for 60 objects.

Following the passing of a pulsation-induced shock wave through the LPV photosphere, the rates of reactions of the relaxing gas are not always sufficiently high to reach the balance conditions prior to the start of the next pulsating cycle. It can be reflected in the light curve due to different effects (such as change of the maximum amplitude, minimum depth, or duration). Particularly, the hump on the light curve can be an observable indication of the shock wave passing [28]. Stars with this peculiar property have a forked structure of their H_2O maser line. If these effects are related, then all stars that have forked structure of the maser line must also have a hump on the light curve, even if not in all cycles of the light variations. It is necessary to statistically study stars with a clear hump, even if the hump occurs only in one cycle.

The same issues concern the semiregular variables. Their investigation is proposed through similar ways, however at first it is necessary to separate all pulsation harmonics, where it is possible, and to derive the time-dependent relations for their amplitudes and frequencies.

The study of LPVs was carried out as a "Stellar Bell" part of the international project "Inter-Longitude Astronomy" [2] in tight cooperation with the "Ukrainian Virtual Observatory" project [43].

ATLASES OF MEAN LIGHT CURVES AND NEAR INFRARED CURVES. CORRELATION ANALYSIS OF MEAN LIGHT CURVE PARAMETERS

For 62 Mira-type stars (in optical band) and 7 Mira-type stars (in near infrared band), the values of periods have been re-determined; the mean curves have been fitted by a trigonometric polynomial with an optimal number of harmonics; a number of light curve parameters have been calculated (amplitude of the current harmonic in magnitudes, phase of the amplitude maximum of the current harmonic, ratio of the harmonic amplitude to the amplitude of the main harmonic wave, the phase shift of the current harmonic with respect to the main wave, the phase shift of the current harmonic with respect to the maximum brightness). Parameters of the sharpness of the both (ascending and descending) branches of the light curve are obtained: the average characteristic times (dt/dm) of the brightness changes by 1^m; maximal slope of the branch (dm/dt); ratios of slopes dm/dt to ones derived for the sinusoidal shape of the light curve with the same amplitude and period. Also asymmetry is derived as the ratio of the ascending branch duration to the period. All these parameters are tabulated in [7, 23].

To obtain the mean light curves of the Mira-type stars, we used observations from the databases of the American Association of Variable Stars Observers published by Mattei [39] and the data by Whitelock et al. [46].

We also presented an atlas of the mean light curves of 34 faint Mira-type stars [25], based on digitized data from the scanned Atlas by Maffei & Tosti[1].

Correlations between the parameters of the light curves for all these LPV stars are studied. In the paper by Andronov & Kudashkina [6], the correlations between twenty-five parameters are discussed.

ANALYSIS OF VARIATIONS OF PARAMETERS OF INDIVIDUAL CYCLES. CORRELATION ANALYSIS OF PARAMETERS OF INDIVIDUAL CYCLES

As light curves of Miras vary significantly from one cycle to another, we did a detailed analysis of their long-term variations and a correlation analysis of the parameters of individual cycles of pulsation. In our sample, approximately 50 Miras, as well as several semiregular (SRa) variables, were presented.

We used observations from the databases of the Association of French Observers of Variable Stars (AFOEV), the Variable Stars Observer League of Japan (VSOLJ), and recently the American Association of Variable Stars observers (AAVSO). This allows to study variability of these stars during a time interval of up to 100 years. The final data are different for different stars, since the databases have been increasing with time. Since the data are a mixture of observations from a large number of observers with individual photometric systems, they show a significant scatter of $0.3^m - 0.5^m$, although the brightness

[1] http://astro.fisica.unipg.it/atlasmaffei/main.htm

accuracy estimates conducted by the most experienced observers were considerably better, down to 0.07^m. Points that differ from the approximation by more than 1.2^m were removed from the initial data sets as "erroneous". Details of the method of processing the original data can be found in [1, 8].

For each cycle of variability, the following basic parameters were determined:

- the times of the minimum and maximum, their phases and magnitudes (two methods were used to determine the times of the extrema: running parabolas (RP) and asymptotic parabolas (AP) as described by Andronov & Marsakova [8]);
- the average time, phase, and magnitude of a hump at the ascending branch (if it is present);
- the values of inverse slopes dt/dm for individual cycles at the ascending and descending branches;
- the times and phases of the intersections of linear segments of the light curve with levels of fixed magnitudes.

Details of calculations of these characteristics were described in the paper [35].

Besides the major parameters, the following related characteristics were calculated:

- the amplitude of the ascending and descending branches (difference in magnitudes at the current maximum and the two corresponding minima — the previous and subsequent ones);
- the period, as the time interval between the successive maxima;
- the period, as the time interval between the successive minima;
- the durations of the ascending and descending branches;
- the asymmetry (two values: the ratio of the duration of the ascending branch to the period between nearby maxima and the period between nearby minima;
- the difference in magnitudes between the successive maxima;
- the difference in magnitudes between the successive minima;
- the average brightness (magnitude) at the ascending and descending branches.

We used the characteristics listed above for correlation analysis [35]. Among these correlations, the most significant are the correlation between the amplitude and the period, as well as between the magnitudes at the maximum and the minimum with the period. Correlations between magnitudes at current and previous maxima characterise the stability of the amplitude and the mean brightness. A correlation with the opposite sign is observed in V Boo, which is characterized by amplitude reduction and change in the character of the variability that is more characteristic of semiregular stars.

Correlations between the magnitudes at current and next minima also can indicate the presence of systematic changes in the average brightness.

The time dependencies of all these characteristics were also studied. Here, the time of the current maximum was ascribed to both periods and asymmetries, while the average of the time between the maximum and the corresponding minimum was ascribed to such characteristics as the amplitude and the average brightness, which are encountered twice in a single cycle.

When necessary, a periodogram analysis was conducted in order to determine the characteristic times for changes of period, amplitude or mean brightness.

The most prominent changes in the mean brightness are detected for Miras of C spectral class [29]. Carbon variables S Cep, U Cyg and V CrB show cyclic changes with characteristic times of approximately several thousand days. A significant decrease of the mean brightness was registered in the carbon star V CrB, S-Mira S Cas, M-Miras R Dra and R LMi, and may be suspected for some others. Mattei & Foster [40] also detected faintening of many stars in their sample, and none of the variables became brighter.

We observed a secular increase in amplitude of 5 stars (including 4 Miras and SS Vir, which has been previously classified as a semiregular star) and a secular decrease in two stars RU Cyg and V Boo, for which the classification as semiregular was confirmed. Coefficients for the amplitude changes with time are listed in the paper [35]. We can, therefore, assume that some Miras are characterized by a secular increase of amplitude (except the stars at the helium flash stage), while some semiregular variables are characterized by a decrease of amplitude.

The secular (progressive) period changes for 4 stars, which presumably undergo the helium flash, were studied by Marsakova & Andronov [33]. The characteristics of these period changes were investigated. T UMi shows a clear increase in the slope dm/dt of the branches of the light curve, R Aql and R Hya show a strong amplitude decrease, mainly due to brightening of minima. If one places these stars in the sequence of changes in the amplitude and slope of the ascending and descending branches of the light curve, this sequence is in a good agreement with the position of the stars at different stages of the helium flash on existing models [47].

The other period changes of other Miras will be described in the next paragraph.

We have also analysed the appearance of the humps at ascending branches of Miras' light curves [36]. All the stars that were studied can be divided arbitrarily into two types: firstly, the stars with large humps, which sometimes appear as secondary maxima (these stars show humps almost in each cycle); secondly, the stars with small humps or "steps", which show these features in a relatively low number of cycles.

As a result, the following conclusions can be made. The parameters of the humps are related to the asymmetry of the curve. The relative duration of a hump correlates especially well with the asymmetry. This result is in good agreement with paper [28]. On average, the number of humps increases for stars with more asymmetric curves. The humps last longer in low amplitude stars. This correlation is observed over the entire sample of stars. The stars of the different spectral classes (M, C, S) are not distinguishable according to this dependence, and nor are the stars which had been previously classified as semiregular.

Characteristics of individual cycles were published in catalogues: for the Mira-type variables by Marsakova & Andronov [32], [34], for the semiregular variables by Chinarova & Andronov [12], and for the RV Tau-type stars the catalogue was announced by Paunzen et al. [42].

Analysis of long-term variability of last mentioned types of variables is illustrated by using the SRb-type variable U Del [4], where two periods of slow (1198^d) and fast variability (119.45^d) were refined, and AF Cyg [5], which was suggested by Kopal [18] to belong to the transitional type between the long-period variables and the RV Tau-type stars.

PERIOD CHANGES OF MIRAS

Many Mira-type variables exhibited changes in their periods. Zijlstra & Bedding [48] defined continuously changing periods, sudden changes, and meandering Miras (whose periods change with time to some extent, followed by a return to the previous period). Our study resulted in a more detailed classification of the period changes [30, 31].

Small irregular period variations are exhibited by a majority of the Mira-type variables.

Many Mira variables, for all the time, or just over certain time intervals, show switchovers between similar period lengths producing the saw-tooth $O-C$ curves. Such evolution is cyclic rather than strongly periodic with characteristic times of about 10 000–20 000^d.

For some variables, smooth cyclic period changes at the timescale of about 17000–22000^d were found.

As it was mentioned above, the progressive period changes (continuous ones of the same sign) are typical for helium shell flash stars.

Some variables have "noisy" $O-C$ curves as a result of multiperiodicity effects. They will be discussed below.

PERIODOGRAM AND WAVELET ANALYSES OF THE AGB SEMIREGULAR VARIABLE STARS

The different types of the semiregular variability using examples of some stars are discussed. Periodogram analysis for nine stars was carried out. The behaviour of the supergiants PZ Cas and S Per was studied in detail, and the radius of S Per was estimated, suggesting that the star pulsates in the first overtone [24].

For the stars RX Boo, RT Vir, SV Peg, TW Peg, BK Vir, U Mon, several values of the periods were redetermined [27].

Time series analysis of the bright cold carbon SR-type star Y CVn were carried out. The star belongs to a rare subclass "J" and has a separate asymmetric envelope. It is assumed that no "S" process takes place in this star. Due to this, Y CVn may belong not to the AGB, but to the RGB stage, or to a stage of helium burning in a nucleus after a helium flash. The data from the published international databases of AFOEV (France) and VSOLJ (Japan) were studied using the periodogram and wavelet analysis and the "running sine" approximations. The cycle of variations is 267^d (varying from 247^d to 343^d), which are superimposed on 1000^d–10000^d waves [26].

Thus, the photometric parameters set (amplitude, mean amplitude, amplitudes of the frequencies completing the multiperiodic oscillation and their character of the dependence versus time) would be used for the detailed classification of semiregular variables [21].

MULTIPERIODICITY

Kudashkina [20] noted that the majority of semiregular variables are multiperiodic. They typically exhibit two periods with their ratio falling within the range of $1.70 \leq P_1/P_2 \leq 1.95$, although some examples of stars that are spread even further apart are known [5].

The group of Mira-type and semiregular variables with similar periodicity (multiperiodicity) was analysed. They have periods of 230–260^d and 140–150^d and show intervals of periodical (Mira-type) variability with a relatively high amplitude and "semiregular" (SR-type) small-amplitude oscillations. Results of periodogram analysis are represented in [38]. The stars have period ratios within the range of 1.65–1.75, which is in good agreement with [20] and [5].

Four variables were analysed in detail in the paper [37]. These variables show not only intervals of "constancy" or a significant decrease in amplitude (in the case of RU And almost to a zero value [9]), but also prominent changes in the phase of pulsations. During the "semiregular intervals", most of them show variability affected by two to three periods.

SYMBIOTIC VARIABLES

Symbiotic variables, which contain a compact star and a red giant, may combine the properties of pulsating long-period variables with the activity of interacting binary systems with accretion effects. As interacting binary systems, they are related to cataclysmic variables, and, as red giants with large dust envelopes, they may be similar to carbon long-period variables with long-term changes of mean brightness at timescales of thousands days. Properties of 20 sure and 6 possible symbiotic Miras are discussed in comparison with the normal Miras by Whitelock [45].

Chinarova [10] discussed long-term variability of symbiotic variables UV Aur, TX CVn, V1016 Cyg and V1329 Cyg. The photographic observations using the Moscow and Odessa plate collections were analysed in this research, in addition to the AFOEV observations. For UV Aur and V1329 Cyg (which are not listed by Whitelock [45]) periodic variations (393^d and about 1000^d, respectively) associated with Mira-type pulsations were revealed. Moreover, for UV Aur, Chinarova [11] detected a long-time wave (6800^d) by using a long series of amateur observations from the AFOEV database. One of the explanations is that the orbital period is close to the pulsation one, thus the accretion rate may be modulated also with an "orbital-pulsation" beat period. Under these assumptions, the orbital period may be estimated to be 371.5^d, but this hypothesis has to be checked using spectral observations.

For V1329 Cyg [15], the main photometrical period of 956.5^d was specified for the post-outburst state (after explosion as a symbiotic Nova) and the secondary period (553^d) was found. A long-term wave of approximately 5300^d was suggested.

For V1016 Cyg, the pulsational period of 450^d is listed by Whitelock [44]. The 5500^d periodicity was interpreted as corresponding to the orbital period [41]. The flares seen with this period are similarly explained by the enhanced mass transfer at the periastron of eccentric orbit.

In the classical symbiotic variable CH Cyg [3], three components of oscillations were studied: the long-term (1840^d), orbital (694^d) and probably pulsation (99.6^d) ones.

For the symbiotic Mira R Aqr, the period of pulsations was specified (387.51^d) and also secondary cyclicity of about 3955^d was detected [13]. The time scale ranges from 7.1 to 34.1 days/mag at the ascending branch, to 25.7–44.6 days/mag at the descending branch.

CONCLUSION

Evidence exists that the physical processes taking place in the star during the observation interval, are reflected on its light curve. However, the mean light curve of the star undergoes the characteristic evolutionary variations (the amplitude is changed, the period and asymmetry are increased, the humps appear at the light curve).

At the present time, the AGB-stage is subdivided into the earlier (EAGB) and thermally pulsing regime (TPAGB) of the He-burning shell [14]. At the TPAGB stage luminosity of the star increases (so M_{bol} decreases). For example, S-stars correspond to the EAGB according to the range of the luminosity and effective temperatures. Thus, one may try to classify the stars using all obtained parameters, determined from the light curve, without use of the relationships between the absolute and apparent magnitude.

Thus, the observational parameters and the correlations between them could be used to estimate the age, mass and other physical characteristics for the AGB stars. Especially interesting is to carry out the study of stability of the mean parameters of the light curves of the Mira-type stars; to estimate the contribution of every harmonic wave, contributing to the total light curve; to determine the role of the hump at the total description of the light curves; to investigate evolution of the hump at the light curve for individual stars; to study the similarity of the photometric characteristics in the SR-type stars and Mira-type stars, bringing them to the physical likeness.

Our research allows to determine various properties of long period variables stars and dependencies between their parameters. Also we propose different ways to classify them. For example, we can use as the criteria the types of long-term period changes, secular amplitude changes, statistical diagrams based on deviations of variability characteristics from one cycle to another as described by Marsakova & Andronov [35] and Marsakova [30].

Also, we offer additional photometric classification of Mira-type stars based on three groups of parameters of the mean light curve: total P, Δm, f — period, amplitude, asymmetry; additional r_k, φ_k, s — wave amplitude curve with frequency $k \cdot f_1$, the phase shift relative to the main wave, the degree of the trigonometric polynomial, approximating light curve and the parameters of the slope $m_i, t_i, m_{is}, m_d, t_d, m_{ds}$ — the slope of the ascending branch, the increase of brightness at 1^m, the difference between the ascending branches from the corresponding branch of the sine wave (index i), the same for the descending branch (index d) [19, 23].

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