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Strong period decrease in the Mira star S Sex: a possible helium-shell flash

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Abstract. Analysis of visual observations of the Mira-type variable star S Sex showed that the period of pulsation has decreased strongly since 1984 from 264.8 days to 249.4 days. The cycle length variations were tested by the method of contingency tables and by the span test, so that random or accumulative errors in the period variation were excluded. Our results are in good agreement with the theoretical models that suggest period decreases due to a flash in the helium-burning shell. The great rate of period change shown by S Sex suggests that this Mira star may now be in an immediate post primary helium-shell flash state.

Key words: stars: individual: S Sex – stars: AGB and post-AGB – methods: data analysis

1. Introduction

Mira variables are pulsating red giant stars that exhibit large amplitudes, in general above 2 magnitudes in the visible range, show long periods, usually from 100 to 700 days, and have masses between 0.5 and 3 $M_{\odot}$. Mira stars lie on the Asymptotic Giant Branch (AGB) of the Hertzsprung-Russell diagram, and represent a late stage in the evolution of stars with intermediate masses. They are evolving through the tip of the AGB on a timescale of hundreds of thousands of years and, as such, are affected by two significant processes: (1) in the interior, helium shell flashes, which cause large variations in their luminosity and period on a timescale of tens of thousands of years, and (2) in the outer layers, pulsation-enhanced mass-loss, which reduces their enveloped masses, and ultimately drives them towards the white dwarf stage. Due to this effect, strong stellar winds eject a considerable amount of material into the interstellar medium, accumulating in a circumstellar shell (see the thorough review by Habing, 1996).

Mean periods of Mira stars are well established. Alard et al. (1996), in a study of 150 Mira-type variables, found that most Mira stars had periods in the interval of 150 to 300 days, about 44% exhibiting periods between 200 and 275 days. The period of S Sex is close to 260 days and, according to the aforementioned study, is a classic Mira-type variable. Small period changes from cycle to cycle are usual in this type of stars, although the mean period remains constant in most cases (Isles & Saw 1987; Percy et al. 1990).

The internal structure of a Mira star is very complex, with a carbon-oxygen core surrounded by a helium-burning shell. Above these layers, there is a hydrogen shell which is consuming the envelope of the star. Every few hundred thousand years, the helium shell suffers thermal instabilities known as "shell flashes" or "thermal pulses", which have relevant consequences on the star's evolution. The period changes to be expected in Mira stars due to evolution can be calculated from such evolutionary models as those of Vassiliadis & Wood (1993). Earlier work by Wood & Zarro (1981) had shown that period changes could be large during certain parts of the helium shell flash cycle, although period variations of this magnitude had been observed in only three Miras (R Hya, R Aql and W Dra). Later, Gál & Szatmáry (1995) found a strong period decrease in the Mira star T UMi, which was also interpreted as a change in luminosity due to a possible flash in the helium-burning shell.

We here present an analysis of the Mira star S Sex, which seems to indicate that this star may be a new candidate. We detect an abrupt period change in S Sex, consistent with a change in luminosity caused by a flash in the helium-burning shell. In particular, the rate of the period change suggests that the state of Mira S Sex is immediate post primary shell flash. S Sex is listed in GCVS as a Mira star with a period of 264.9 days, an amplitude of 8.2 to 13.7 in the V-band, and spectral type M2e-M5e.

2. Observational data

The individual observational data for S Sex were taken from various sources: Japanese VSOLJ (Variable Star Observers League), Barnes & Barnes (1971), Kholopov et al. (1985) and some data were obtained by the authors. Some visual data from the French AFOEV were also used to contrast our own observational results. A total of 684 individual observations were initially considered, corresponding to an interval of approximately 92 years (JD2417563 - JD2451340).

The collected data are not distributed homogeneously, because there are many cycles with only few or even no observa-

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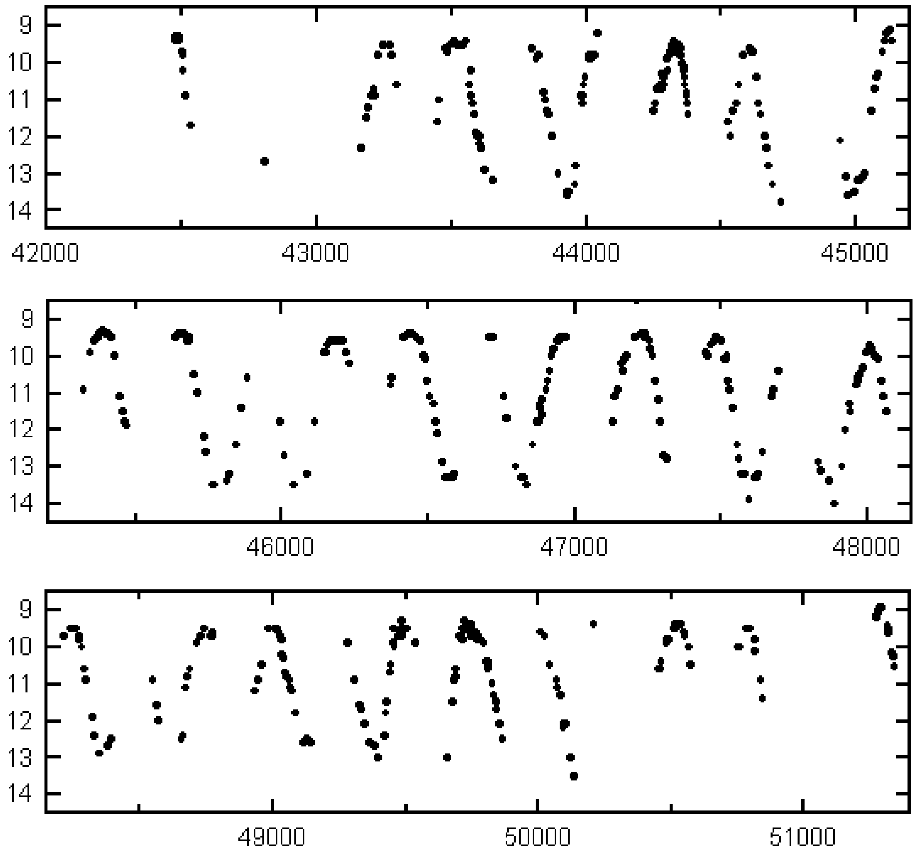


Fig. 1. Light curve of S Sex between JD2442000 and JD2451340.

tions. Also, the first group of observations, from JD2417563 to JD2419182, includes few data and the uncertainties are large perhaps due to the faintness of S Sex. These data were therefore not included in the detailed study of the period change, although they will be discussed in the final section in order to give an overview of the temporal evolution of S Sex. Fig. 1 shows the light curve from JD2442000 to JD2451340.

We made new high-precision observations of S Sex in order to confirm its period change, using differential photometry for 15 nights between April 5 and June 10, 1999, at the Observatorio del Departamento de Física (Universidad de Extremadura, Badajoz, Spain). These observations were carried out in the Kron-Cousins system V band with a 0.4-m Newton reflector equipped with a Starlight Xpress CCD Camera based on the chip SONY ICX027BL 6.1 x 4.35 mm^2. The star GSC4912.137 (V = 9.378) was employed as comparison, and GSC4912.627 (V = 12.3) as a check star. The comparison star had constant brightness during the observations.

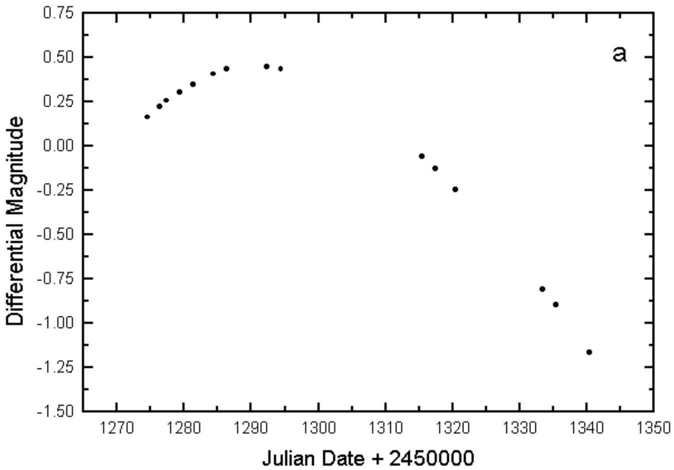
Figs. 2a and b display the light curve obtained by us using CCD photometry and by the AFOEV using visual photometry in 1999, respectively. Comparison of the two curves allows one to estimate the precision of times of maxima based on the visual data taken from the VSOLJ data source. The individual CCD data obtained by us for each night are presented in Table 1. The mean precision accuracy of these observations is about 0.008 magnitudes, significatively smaller than the precision of the AFOEV visual data, which is of the order of 0.15 magnitudes.

Table 1. Differential magnitudes (variable minus comparison) observed for S Sex in 1999, using CCD photometry.

HJD	ΔV
2451274.5	-0.164 ± 0.010
2451276.4	-0.224 ± 0.010
2451277.4	-0.257 ± 0.006
2451279.4	-0.305 ± 0.010
2451281.4	-0.350 ± 0.003
2451284.4	-0.409 ± 0.007
2451286.4	-0.437 ± 0.008
2451292.4	-0.446 ± 0.004
2451294.4	-0.435 ± 0.009
2451315.4	0.058 ± 0.010
2451317.4	0.128 ± 0.009
2451320.4	0.243 ± 0.008
2451333.4	0.809 ± 0.011
2451335.4	0.897 ± 0.012
2451340.4	1.162 ± 0.006

3. Results

The observations were then initially separated into six segments each covering about five years, and the mean period for each segment was evaluated by Fourier analysis. Each segment includes 7 to 10 cycles, depending on the number of data and the well-defined maxima and minima that exist in the interval. Table 2 shows the data series intervals and the resulting mean periods.



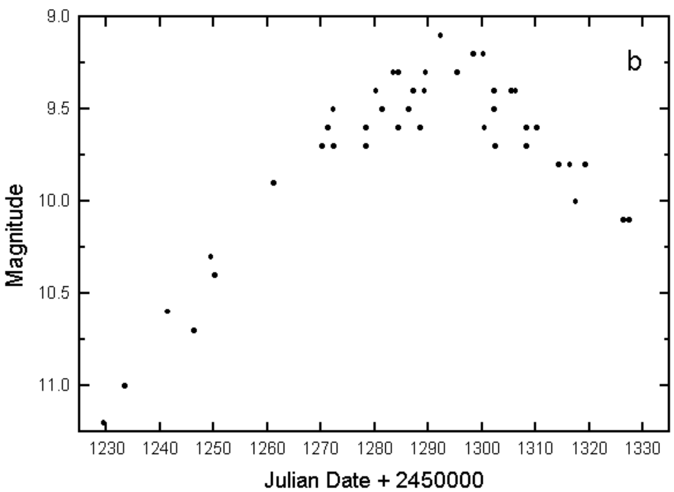


Fig. 2a and b. Light curve at maximum for S Sex obtained **a** by the authors using a CCD camera, **b** by the French AFOEV using visual data.

The uncertainty in the period determination was estimated to be around 4 days in most cases.

The analysis of the first two segments gave a similar mean period of 262.3 and 263.1 days, respectively, in perfect agreement with the period of 262.9 days given by Barnes & Barnes (1971) at JD2440619. In the third data series we found a mean period of 264.8 days, also coherent with the period of 264.9 days given in Kholopov et al. (1985) at JD2445390. The fourth and fifth data series, however, gave mean periods considerably shorter than those observed in the first three series, clearly showing a period decrease. In particular, the mean period obtained for the fifth segment was 249.4 days.

The analysis of the sixth data interval yielded a period of 251.8 days, somewhat longer than the mean period observed in the preceding series, indicating a possible period increase in this interval. This increase, although small, seems to be confirmed by our observations. From the last maximum included in the VSOLJ data base (JD2450527.8) and the maximum obtained from our observations (JD2451289.5), we determined a single mean period of 253.9 days for the last 2 years.

Table 2. Data series intervals considered and resulting mean periods.

$Time interval (JD)$	$Period (Days)$
2428567.1–2434062.9	262.3
2442475.1–2443655.0	263.1
2443798.3–2445760.2	264.8
2445770.1–2447870.4	257.9
2447883.3–2449538.0	249.4
2449284.3–2450844.2	251.8

Table 3. Maxima obtained from the light curve of S Sex and O−C residues relative to the ephemerides of reference.

$Maximum (JD)$	$(O-C)_I$	$(O\text{-}C)_{II}$
2440619.0	0	−2.8
2442485.2	25.9	9.1
2443259.5	11.5	−11.3
2443519.2	8.3	−16.5
2444329.1	29.5	−1.3
2444599.6	37.1	4.3
2445123.9	35.6	−1.2
2445390.0	38.8	0
2445652.6	38.5	−2.0
2446184.4	44.5	−3.0
2446442.6	39.8	−7.0
2446968.4	39.8	−11.0
2447226.6	35.1	−17.7
2447484.0	29.6	−25.2
2448000.5	20.3	−38.5
2448247.2	4.1	−56.7
2448749.7	−19.2	−84.0
2449002.6	−29.2	−96.0
2449754.4	−66.1	−138.9
2450520.8	−88.4	−167.2
2451289.5	−108.4	−193.2

I Ephemeris given by Barnes & Barnes (1971).
II Ephemeris given by Kholopov et al. (1985).

Table 3 lists the well-defined maxima and the O−C values calculated from two ephemerides. Figs. 3a and b display the O−C values versus Julian date. Ephemeris are given by the following expressions:

Max = JD2440619 + 262.9·E (Barnes & Barnes 1971)
Max = JD2445390 + 264.9·E (Kholopov et al. 1985)

From these figures, one can clearly appreciate the period change that S Sex underwent around the epoch JD2446140. However, in the case of Mira-type stars, any study of O−C residues may be complicated by the existence of significant errors. The accumulated difference between each observed period and the period assumed in the ephemeris makes the points drift well away from a straight line and may give the impression of period changes. Such errors are known as "cumulative errors". Another problem associated with long-period variables is the observational error in the estimation of maximum luminosity. Because each maximum is common to two cycles, a wrong es-

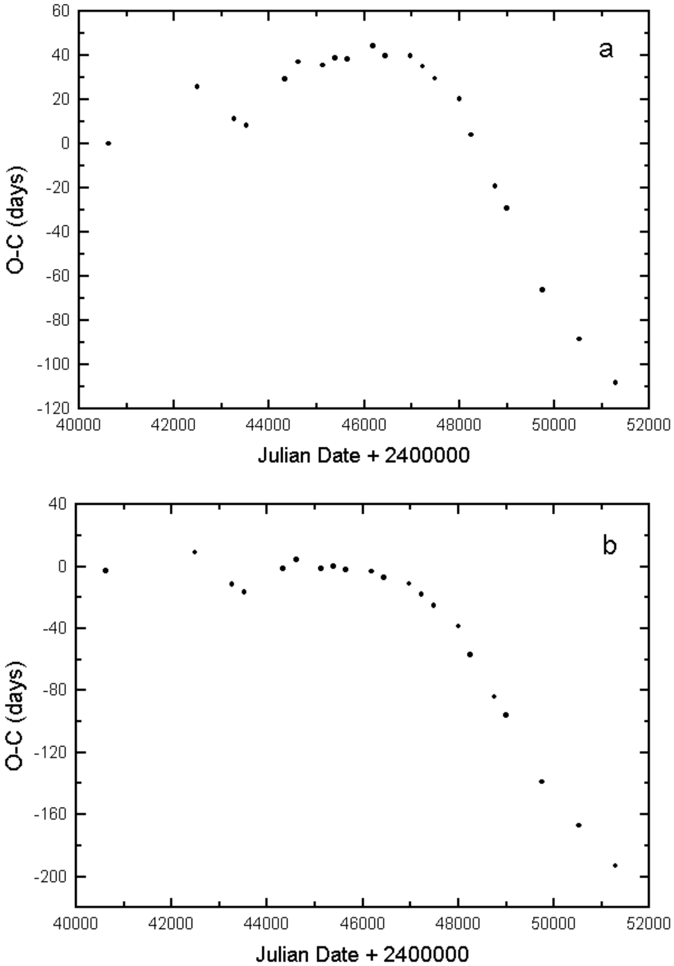


Fig. 3a and b. O−C residues obtained from the ephemeris given by: **a** Barnes & Barnes (1971); **b** Kholopov et al. (1985).

timate of its position will increase the length of one cycle and decrease the length of the next cycle. These errors are known as "random errors".

These problems have a long history of study (e.g., Sterne & Campbell 1937; Lacy 1973; Isles & Saw 1987, 1989a and 1989b; Lloyd 1991), with several general methods having been developed to detect real changes in the mean period. We tested the cycle lengths for change in S Sex by the method of contingency tables described in Lacy (1973). It seems that there is no doubt about a change in the period of S Sex since we obtained a very large value for the χ_c^2 parameter of 27.84. This parameter has a χ^2 distribution with one degree of freedom, and indicates that the change in the period of S Sex is significant at 99%. The application of the contingency tables method then indicated that the change in period was not due to random or cumulative errors. In addition, the span test gave similar results: by assuming a mean period derived from the first and last maximum for different data groups, all the observed greatest $|(O\text{-}C)|$ values into each data group were much higher than we might expect to get by chance if the mean period does not vary.

Fig. 4 represents the period decrease rate of S Sex. The individual periods were obtained from the well-defined max-

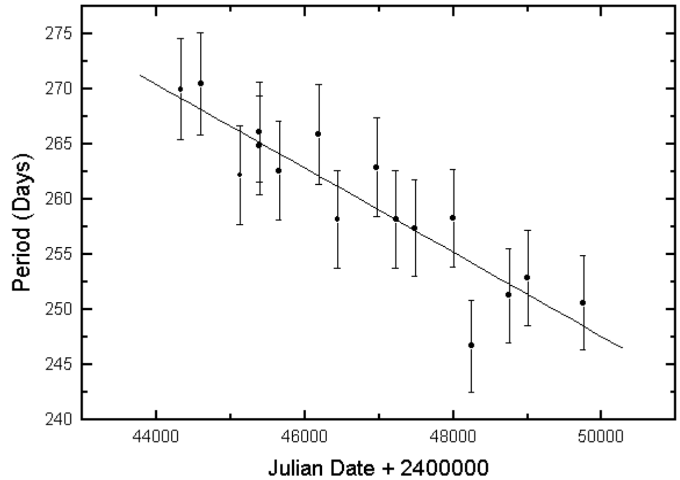


Fig. 4. Period of S Sex as a function of time. Line denotes the linear fit to individual periods. Error bars are about 2% of the period.

ima given by the VSOLJ data base, Barnes & Barnes (1971), Kholopov et al. (1985) and our observations. The individual cycle lengths were calculated from maximum to maximum when possible. In some cases they had to be determined without using consecutive maxima. Although a certain degree of dispersion is involved, Fig. 4 denotes a fast change in the period of S Sex. The mean rate of the period variation was obtained by performing a simple least squares fit to the period data obtained between JD2444329 and JD2449754, giving a value of dP/dt = 0.0038 day/day with a regression coefficient of r = 0.90.

4. Discussion and conclusions

Several works in the literature have described possible cyclic period changes detected in some Mira-type stars through the study of O−C residues. However, most of these period changes were not as strong as here detected for S Sex. A study of the Mira star T UMi by Gál & Szatmáry (1995) showed similar or even somewhat greater period variations than observed for S Sex in the present work. The theoretical models locate T UMi as just after the beginning of a helium shell flash. Until now, only the stars T UMi, R Aql, R Hya and W Dra (Wood & Zarro 1981) seem to have undergone abrupt period changes associated with this transitional evolutionary state. These stars are interesting as test cases for the theoretical models that interpret such changes as a flash in the helium-burning shell. Such a flash certainly has to be regarded as a possible cause of the strong period decrease that we observed in S Sex.

Indeed, several aspects give further evidence for a helium-flash process in S Sex. The data collected from 1907 to 1999 can be arranged into three well-defined parts that may give an overall vision of the stages of S Sex's evolution. The first corresponds to the oldest observations, between 1907 and 1911. The data are sparse in this interval, so that it is not possible to give a reliable period. The best estimate seems to be around 260 days. We did not observe significant period changes in the second part, from 1936 to 1983: the mean period changed only within a range of 2.5 days over 47 years. Such period stability is consistent with the theoretical models of AGB stars in the phases prior to a helium flash process, which predict a very small luminosity increase over several tens of thousand years as a consequence of a stable process of hydrogen-shell burning.

When the helium flash occurs, the hydrogen-burning shell is rapidly extinguished causing a sudden drop in the star's surface luminosity and a strong decrease in period. Our results are in good agreement with the predictions of theoretical models for this stage. Indeed, the third group of observations, from 1983 to 1994, were characterized by a sudden drop in the period of the star (as well as in luminosity) of the order of 20 days in only 11 years. Taking into account the period-luminosity relation given by Wood & Zarro (1981), we can estimate the luminosity drop detected for S Sex. The luminosity variation can be evaluated as a function of the period variation by assuming values for the b and β coefficients in the period-luminosity relation. A value of β = 16.67 was adopted here, according to the old disk giant branch of Eggen (1975) and a value of b = 2.0 derived from the linear, nonadiabatic pulsation calculations for luminous giant stars, values assumed by Wood & Zarro (1981). With these assumptions, S Sex would present a luminosity decrease of somewhat more than 6% in the helium flash stage. It must be noted that although most Mira-type variables do not present strictly constant periods, their period variations are less than about 2% over time intervals of 10 to 50 years (Plakidis 1932; Wood 1975).

Also assuming the helium flash theory, a further hypothesis could be considered. The models predict that after the first helium flash and subsequent diffusion of energy, a second weaker flash in the helium shell occurs, so that the observed period variation in S Sex could be associated with this weaker flash. However, the secondary flash usually produces a smaller change in luminosity, so that the period change rate observed for S Sex would be more in accordance with a primary helium flash. Another possibility is that S Sex is, in fact, a binary system. According to Lewis (1992), some Mira stars without 1612 MHz OH maser activity are binaries with a white dwarf companion, although we could not test this hypothesis because of the lack of other observations to be found in the literature.

In summary, our conclusion is that the period change observed in S Sex may be due to a change in luminosity resulting from a helium flash in the helium-burning shell of this Mira. The high rates of change in period and, therefore, in luminosity, suggest that S Sex could now be in an immediate post helium flash state, according to the theoretical models developed for AGB stars.

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