A NEW PULSATING VARIABLE STAR IN LYNX

Fiacconi, Davide[1]; Tinelli, Luciano[2]

1) Carnate (MB), Italy, Gruppo Astrofili Villasanta, davide.fiacconi@gmail.com
2) Usmate (MB), Italy, Gruppo Astrofili Villasanta, luciano.tinelli@fastwebnet.it

Abstract: We report the discovery of a new variable star in the Lynx constellation. The star is catalogued as GSC 03409-00999 ($07^{\mathrm{h}}\ 33^{\mathrm{m}}\ 08.6^{\mathrm{s}}$; $+48^\circ\ 03'\ 53.5''$). From analysis of the light curve we are induced to think the star may be a RRab Lyrae-type variable. We calculated the epoch $\mathrm{HJD}_0 = 2455644.363 \pm 0.007$ and the period $P = 0.61971 \pm 0.00003$ d, during which the star changes its brightness from a minimum magnitude $\mathrm{m_{min}} = 13.65 \pm 0.01$ to a maximum one $\mathrm{m_{max}} = 13.11 \pm 0.01$. The light curve shows the asymmetry 0.248 ± 0.001, with a rise time $\tau_{\mathrm{RT}} = 0.1539 \pm 0.0007$ d.

1 Data acquisition and reduction

All images were taken from Usmate-Velate[1] using a 203 mm Schmidt-Cassegrain reflector ($f/6.3$) equipped with a CCD camera Starlight-Xpress SXV-H9 in standard V-band. Because of sky pollution and technical problems with guide at this focal length, images were exposed 60 s in binning 2×2. Images were also slightly defocused to be able to integrate longer without risk of saturating the detector. The main features of the observing nights are resumed in table 1. We collected 1599 observations in 11 observing nights.

#	Date (HJD)	Time Interval (HJD)	N° of images	t_{exp} (s)
1	2455643	0.274627 - 0.441757	216	60
2	2455644	0.291575 - 0.468862	165	60
3	2455645	0.291303 - 0.469253	228	60
4	2455653	0.290646 - 0.439562	120	60
5	2455654	0.279041 - 0.433157	168	60
6	2455658	0.287671 - 0.411203	102	60
7	2455661	0.300523 - 0.440572	117	60
8	2455662	0.293456 - 0.452301	118	60
9	2455669	0.302506 - 0.422240	86	60
10	2455670	0.310968 - 0.416954	126	60
11	2455673	0.301479 - 0.422601	153	60

Table 1: Summary of observing nights. From left to right: night label, date in heliocentric Julian day based on UTC, time interval of images in HJD, number of images for each session, exposure time of pictures in seconds. All images are in binning 2×2.

In figure 1 is shown the stellar field around GSC 03409-00999 ($07^{\mathrm{h}}\ 33^{\mathrm{m}}\ 08.6^{\mathrm{s}}$; $+48^\circ\ 03'\ 53.5''$) and the three stars used as references, the main properties of which are reported in table 2, taken from GSC 2.3 catalog (Lasker et al., 2008). Image reduction was performed using the software Iris[2]. For each science frame, bias and dark frame subtraction and flat field division were applied.

[1] Usmate-Velate (MB), Italy, lat: $45^\circ\ 35'\ 33''$ N, long: $+9^\circ\ 21'\ 33''$ E, alt: ~ 250 m
[2] IRIS by Christian Buil: http://www.astrosurf.com/buil/us/iris/iris.htm

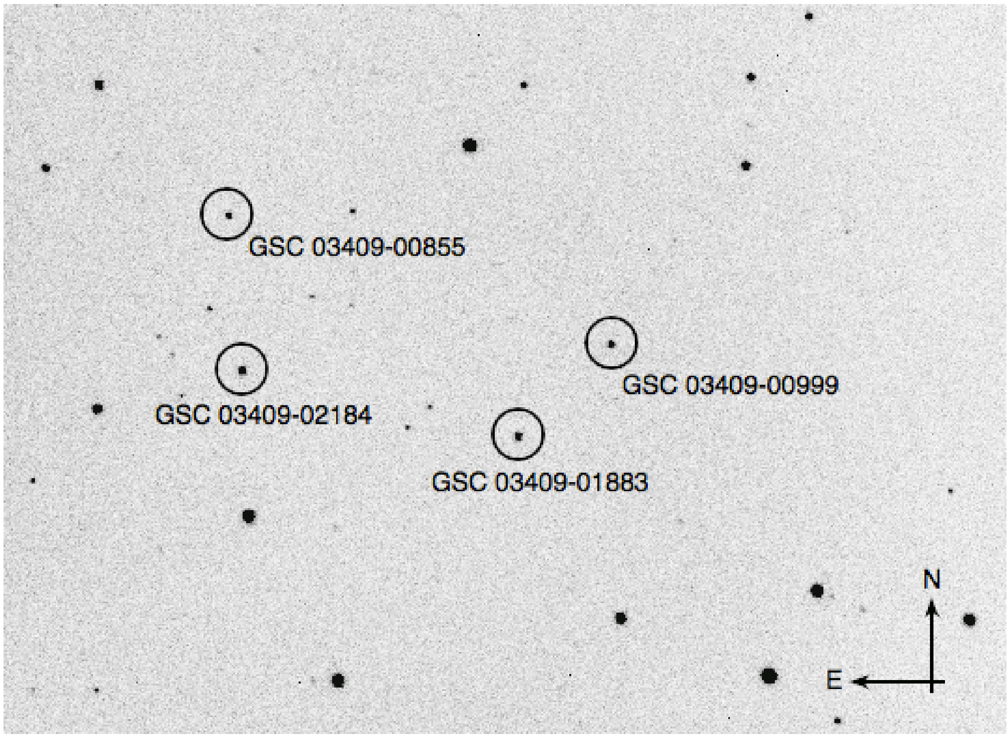

Figure 1: Stellar field of GSC 03409-00999. Reference stars are marked. The field of view is approximately $24' \times 18'$.

Name	Comparison	RA (hh:mm:ss.ss)	Dec (±dd:mm:ss.s)	B (mag)	V (mag)	$B-V$ (mag)
GSC 03409-00855	Ref1	7:33:55.23	+48:03:17.2	14.24	13.34	0.90
GSC 03409-02184	Ref2	7:33:57.14	+48:06:33.9	14.07	12.40	1.67
GSC 03409-01883	Ref3	7:33:20.28	+48:01:55.5	13.53	12.34	1.20

Table 2: Comparison stars for GSC 03409-00999. From left to right: name, label, right ascension, declination (both J2000), B-magnitude, V-magnitude and $B-V$ color. Data are taken from GSC 2.3.

Aperture photometry was used to calculate the instrumental magnitude $\mathrm{m_{inst}}$ of all four stars and we evaluated a typical uncertainty $\sigma_{\mathrm{m_{inst}}} \simeq 0.05$ mag from the scattering on differential instrumental magnitudes between comparison stars during each night.

Since we have data in only V-band, we calibrated instrumental magnitudes in standard ones without a color term, solving for equation:

$$\mathrm{m_{inst}} = \mathrm{m_V} - Z_V - k_V \cdot X, \tag{1}$$

where $\mathrm{m_V}$ are standard magnitudes, Z_V is the zero point, X is the air mass and k_V is the extinction coefficient, all in V-band. We obtained Z_V and k_V by fitting Eq. 1 with Ref1 (GSC 03409-00855) data for each observing night. We chose to use only this star to calibrate Eq. 1 because Ref1 has the $B-V$ color most similar to that of GSC 03409-00999 (~ 0.80 mag, GSC 2.3), hence to minimize eventual biases due to stellar colors. In figure 2 the fits of Eq. 1 for each night are shown, while fits results (Z_V and k_V) with errors are reported in table 4. Then, we converted GSC 03409-00999 magnitude from instrumentals

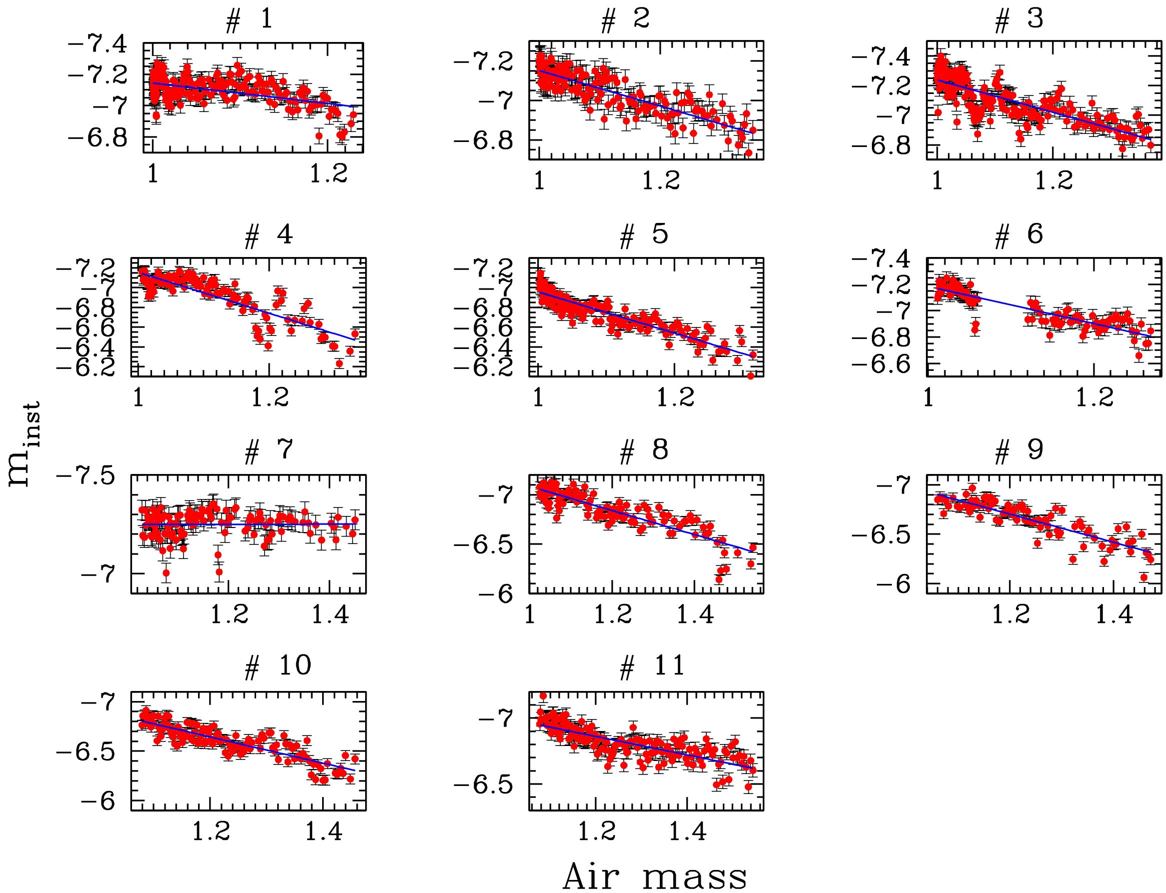

Figure 2: From top left to right bottom: linear fit of Eq. 1 with data of Ref1 for each night, labeled in the figure by the #. Air mass X are on abscissa, while instrumental magnitude $m_{\rm inst}$ are on ordinate.

#	Z_V (mag)	σ_{Z_V} (mag)	k_V (mag/air mass)	σ_{k_V} (mag/air mas)
1	21.13	0.05	0.65	0.05
2	21.38	0.04	0.90	0.04
3	21.66	0.04	1.09	0.03
4	22.56	0.06	2.07	0.05
5	22.37	0.05	2.08	0.05
6	21.93	0.07	1.41	0.06
7	20.58	0.05	-0.01	0.04
8	21.64	0.04	1.22	0.03
9	21.75	0.06	1.42	0.05
10	21.57	0.05	1.33	0.04
11	21.04	0.04	0.70	0.03

Table 3: Results of the fit showed in figure 2. From left to right: night label, zero point Z_V with error σ_{Z_V} and extinction coefficient k_V with error σ_{k_V}.

($\mathrm{m}_{\mathrm{inst},i}$) to standards ($\mathrm{m}_{V,i}$) and we calculated for each image i the uncertainty:

$$\sigma_{\mathrm{m}_{V,i}} = \sqrt{\sigma^2_{\mathrm{m}_{\mathrm{inst}}} + \sigma^2_{Z_V} + X_i^2 \cdot \sigma^2_{k_V}}, \quad (2)$$

where X_i is the air mass corresponding to $\mathrm{m}_{V,i}$ and σ_{Z_V} and σ_{k_V} are, respectively, the uncertainties of Z_V and k_V during the same night of $\mathrm{m}_{V,i}$. We finally discarded some clearly outlier measurements and got a total of 1573 data points. We also converted all times from geocentric to heliocentric Julian dates based on UTC (HJD).

2 Light curve analysis

We calculated an analytical expression for the light curve of GSC 03409-00999 using a trigonometric polynomial approximation of the form:

$$\Psi(t) = A_0 + \sum_{n=1}^{N} A_n \sin\left(2\pi n\nu t + \phi_n\right). \quad (3)$$

We wrote a Python code to perform the non-linear fit of Eq. 3 using the Levemberger-Marquardt algorithm, with an initial estimation of the main frequency ν based on the highest peak of a Date-Compensated Discrete Fourier Transform (DCDFT; Ferraz-Mello, 1981). Uncertainties on all quantities were calculated by Monte Carlo (MC) simulations as in Fiacconi & Tinelli (2009): during each iteration, we generated a synthetic data set as gaussian smearing of the original light curve and we fitted Eq. 3 with these new data. Then, we got the distribution of the fit parameters and we deduced uncertainties as errors on the average.

To decide to optimal value of the maximum order N of $\Psi(t)$, we performed various fits with $N = 1, 2, 3, \ldots, 8$, using one hundred MC iterations to estimate uncertainties. In figure 3 two plots are shown: the left panel shows the probability to obtain *accidentally* a chi-square χ^2 with $\nu(N)$ degrees of freedom greater (i.e., worst agreement, assuming that the fitting model $\Psi(t)$ is adequate) than the observed χ^2_{obs} versus the max order N. The

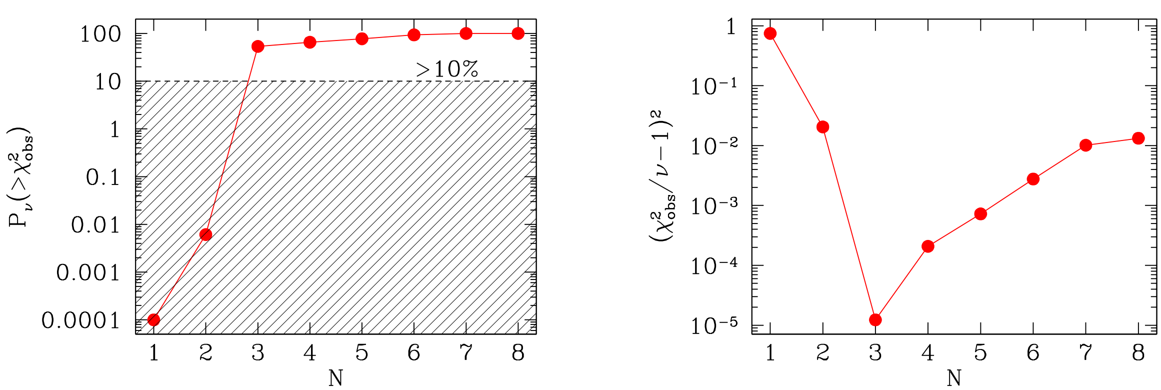

Figure 3: Left panel: probability to obtain a chi-square χ^2 with $\nu(N)$ degrees of freedom greater then the observed χ^2_{obs} in function of the maximum order N of the trigonometric polynomial $\Psi(t)$. Right panel: quadratic relative variation between χ^2_{obs} and the expected value $\nu(N)$ in function of N.

right panel shows the quadratic relative variation between χ^2_{obs} and the expected value

$\nu(N)$ in function of N. Both plots suggest that the most significant value for N is $\sim 3-4$. In fact, assuming a tolerance of $\sim 10\%$, left panel states that N must be $\gtrsim 3$ to overcome the threshold. However, right panel remarks that $\chi^2_{\rm obs}$ approaches its expected value for $N = 3$ or $N = 4$. Hence, $N = 3 - 4$ seems to be the most statistically significant values for the max order of the trigonometric polynomial $\Psi(t)$ and we decide to use $N = 4$. Then, we performed the fit of Eq. 3 with $N = 4$ and we estimated uncertainties with one thousand MC iterations. From the bet-fit value of the frequency ν with error, we estimated the period:

$$P = 0.61971 \pm 0.00003 \text{ d.} \tag{4}$$

In table 4 are reported the amplitudes and phases of the sinusoidal components of $\Psi(t)$, while in figure 4 is shown the phase-scaled light curve of GSC 03409-00999 with the fitted model superimposed.

n	A_n (mag)	σ_{A_n} (mag)	ϕ_n (rad)	σ_{ϕ_n} (rad)
0	13.420365	0.002071	-	-
1	0.216923	0.000353	0.454009	0.029199
2	-0.091086	0.000946	0.280416	0.058608
3	-0.046111	0.001488	0.789775	0.237140
4	-0.016393	0.000685	0.436418	0.325557

Table 4: In table are reported the amplitudes and phases with errors of the sinusoidal components of Eq. 3. From left to right: order of the component, amplitude, amplitude uncertainty, phase and phase uncertainty.

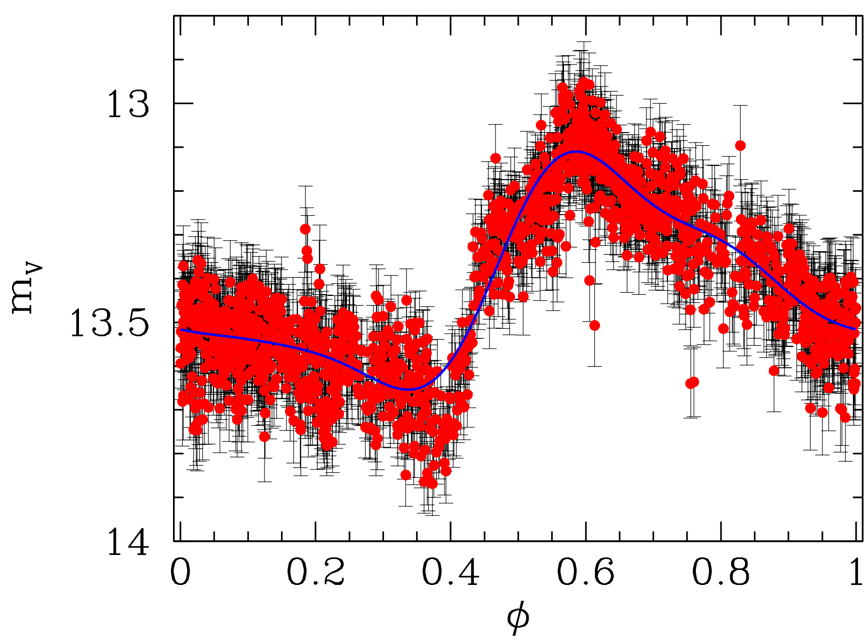

Figure 4: Phase curve of the star GSC 03409-00999. The blue curve is the best fit of Eq. 3, the parameters of which are reported in table 4.

Despite the scattering on light curve points, the curve resembles the one of a pulsating variable. In particular, we are induced to think the star could be a RRab Lyrae-type pulsating variable, as described in the General Catalogue of Variable Stars (GCVS; Samus et al., 2009): "[RRab are] RR Lyrae variables with asymmetric light curves (steep ascending branches), periods from 0.3 to 1.2 days, and amplitudes from 0.5 to 2 mag in V". We derived the magnitude excursion (minimum and maximum magnitude, m_{min} and m_{max} respectively) and the asymmetry (phase difference between the times of maximum and minimum, $\alpha = \phi_{max} - \phi_{min}$) of the light curve from the solution $\Psi(t)$. Results are reported in table 5 with uncertainties based on the one thousand MC simulation performed to deduce fit errors: as previously did, from each synthetic data set we deduced the distribution of m_{min}, m_{max} and α and we toke the error on the average as uncertainty. The light curve

Parameter	Value	Uncertainty
m_{min}	13.65	0.01
m_{max}	13.11	0.01
α	0.248	0.001

Table 5: In the table are reported the main shape parameters of the light curve with uncertainties. From the first row: minimum magnitude, maximum magnitude and asymmetry.

is quite asymmetric, with a rise time $\tau_{RT} = 0.1539 \pm 0.0007$ d ($\sim 25\%$ of the period).

From observation #2, we measured a time of maximum to deduce ephemerides for this star. First, we tried to fit the maximum using polynomial of various degrees (from 2 to 7), but the high scatter in the measurements prevents us from reaching an accurate result. Hence, we decide to evaluate this maximum time by means of the solution $\Psi(t)$. We deduce a maximum time:

$$\mathrm{HJD}_0 = 2455644.363 \pm 0.007, \tag{5}$$

where the uncertainty was estimated as the error on the average of one thousand synthetic maxima calculated from MC simulations. Then, we propose the linear ephemerides:

$$\mathrm{HJD}_{max} = 2455644.363(7) + 0.61971(3) \times E, \tag{6}$$

where numbers inside brackets are the uncertainties expressed in units of the last digit.

3 Conclusion

We reported the discovery of a new variable star in Lynx, GSC 03409-00999. The fit of the light curve with a trigonometric polynomial provided an estimation of the period:

$$P = 0.61971 \pm 0.00003 \text{ d}.$$

We calculated the ephemerides:

$$\mathrm{HJD}_{max} = 2455644.363 + 0.61971 \times E.$$

The star changes its brightness from $m_{min} = 13.65 \pm 0.01$ to $m_{max} = 13.11 \pm 0.01$ with a rise time $\tau_{RT} = 0.1539 \pm 0.0007$ d, corresponding to $\sim 24.8\%$ of the period. From the analysis of the light curve we think that GSC 03409-00999 could be a pulsating variable, in particular a *RRab Lyrae-type variable stars*. This could be confirmed provided spectroscopical data. Moreover, longer observations could show if this star has long-term period variations or amplitude modulations.

References

Ferraz-Mello, S., 1981, *AJ*, **86**, 619-624, 1981AJ.....86..619F

Fiacconi, D., Tinelli, L., 2009, *OEJV*, **114**, 1, 2009OEJV..114....1F

Lasker, B. M., et al. 2008, *AJ*, **136**, 735, 2008AJ....136..735L

Samus, N.N., Durlevich, O.V., et al., 2007, *General Catalogue of Variable Stars*, 2009yCat....102025S