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First time-resolved CCD photometry and time-series analysis of NSV 13601

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Abstract We present the first results of a time-resolved CCD photometric and time-series analysis of NSV 13601, a variable star in the constellation Pegasus. The $14''$ Schmidt-Cassegrain telescope of Maharaja Krishnakumarsinhji Bhavnagar University (MKBU) was used for observations. Analysis was performed both in VStar and Period04 software, and their results were compared. The main results are as follows: From data analysis, its has period ∼77.784 d (MKBU data V) (VStar), ∼77.632 d (MKBU data Ic) (VStar), ∼77.058 d (MKBU data V) (Period04) and ∼49.560 d (MKBU data Ic) (Period04). Its V and I mean magnitudes for MKBU data are 12.203 (V) and 11.292 (I) mag respectively. We confirm it to be a variable star.

Key words: Stars: individual: NSV 13601 — stars: oscillations — techniques: photometric

1 INTRODUCTION

NSV 13601[1] (RA: 21:13:01.24, DEC: +18:56:29.2) is an eclipsing binary type variable star in the constellation Pegasus.

Many astronomical databases were searched for collecting details about this star, and the details are given below:

In the VSX database[2], it is designated as a suspected variable with Mag. (11.31 – ? V) and has variability type E. Its other names are 2MASS J21130123+1856292, GSC 01658-00370 and TYC 1658-370-1.

In the GCVS database[3], its type is E, magnitude range is Max. ∼13 and Min. < 13.5.

Many other astronomical databases, like CDS portal[4], CRTS DR3[5], Catalina survey[6], Hipparcos[7], Hipparcos Main Catalog[8], DASCH (apass) Catalog[9], Gaia[10], Hipparcos-2[11], ASAS-SN[12] and AAVSO[13], were searched, but no relevant information was found about NSV 13601.

After collecting all these pieces of information about the target star, a finder chart was prepared from the AAVSO star chart plotter along with its photometry table. The comparison and check stars were selected from the table nearest to the variable star and with magnitude very close to the target variable star. All the three stars were in the same CCD frame.

The standard CCD differential photometry was performed and details about the variable star, comparison star and check star are provided in Table 2. Also, the Maharaja Krishnakumarsinhji Bhavnagar University (MKBU) CCD (V) image is displayed in Figure 1.

A total of 34 nights worth of data was collected and the total numbers of frames were 170 each in the (V) and (Ic) filters.

Light curves (LCs) were prepared for MKBU Data-V and MKBU Data-Ic as depicted in Figures 2 and 5 respectively, for further time-series analysis.

[1] *https://www.aavso.org/vsx/index.php?view=detail.top&oid=52225*
[2] *https://www.aavso.org/vsx/*
[3] *http://www.sai.msu.su/gcvs/cgi-bin/search.htm*
[4] *http://cdsportal.u-strasbg.fr/*
[5] *https://crts.iucaa.in/CRTS/*
[6] *http://crts.caltech.edu/*
[7] *https://www.cosmos.esa.int/web/hipparcos*
[8] *https://heasarc.gsfc.nasa.gov/W3Browse/all/hipparcos.html*
[9] *http://dasch.rc.fas.harvard.edu/index.php*
[10] *https://www.cosmos.esa.int/web/gaia/dr2*
[11] *https://www.cosmos.esa.int/web/hipparcos/hipparcos-2*
[12] *https://asas-sn.osu.edu/variables*
[13] *https://www.aavso.org/data-download*

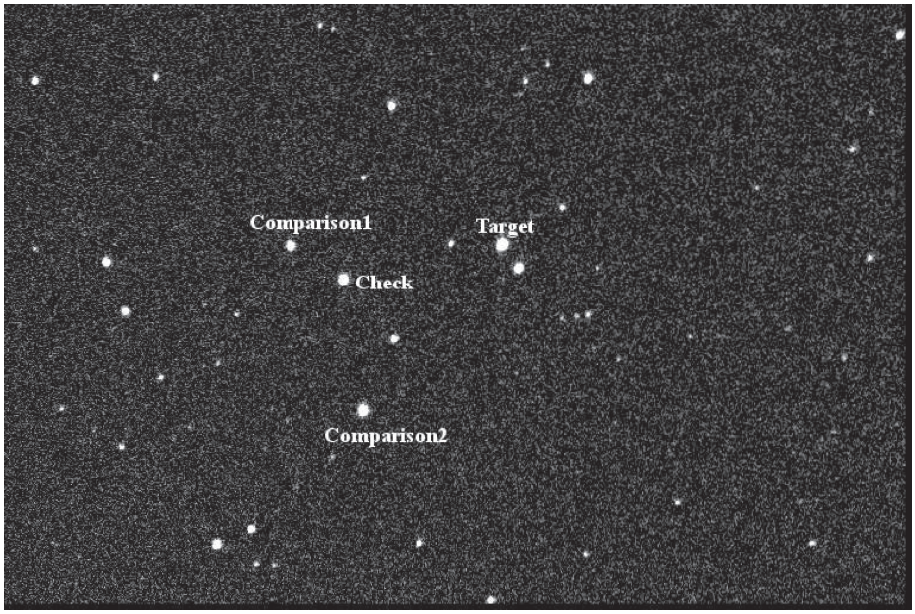

Fig. 1 Object, check and comparison star field-CLEAR Filter: 16–04–2014.

2 METHODOLOGY

2.1 Instrumentation

All the photometric data analyzed for this paper were obtained using a $14''$ optical telescope, a Celestron Schmidt-Cassegrain reflector telescope mounted at MKBU Observatory, Bhavnagar (Lat: 21.7542°N; Long: 72.1304°E), India[14] (Bhatnagar et al. 2001).

The automated observatory houses the telescope (D = 355.6 mm, f = 3910 mm, f/11) on an equatorial mount. The telescope has an SBIG ST-7XME CCD camera (Table 1) along with an SBIG CFW-8A filter wheel with Johnson-Cousins $UBVRI$ photometric filters[15] (Bessell 1990). The telescope has two stepper motors (Aerotech Model 310SML3) for RA and DEC axes which are controlled by micro-stepping stepper motor translators (Aerotech DM8010). The whole system was indigenously developed in collaboration with the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune[16]. For telescope control, SCOPE (by Mel Bartel) was implemented in conjunction with Cartes Du Ciel. There is a USB connection between the CCD and PC for data as well as commands. Astronomy data are locally stored on the PC. A GPS receiver is also connected to the PC, which periodically updates the clock on the computer.

Table 1 Technical Details of MKBU Telescope System with Focal Reducer

CCD camera	SBIG ST-7XME
Telescope	Celestron $14''$ f/11
Reducer	0.63×Reducer
Pixel Binning	1×1
Image scale	0.75 arsec pixel^{-1}
Focal length	2463 mm
Focal ratio	76.93
Field of view of CCD camera	$9.6' \times 6.4'$ (arcmin, width × height)

The stepper motors are mechanically coupled to the telescope through a friction drive with ratio 1:24. Thus, movement of the telescope is finely controlled by the stepper motor to the tune of 25 000 steps per rotation in both axes, resulting in about 2.16 arcsec per step accuracy. A friction drive was selected to avoid backlash. The friction drive wheels with 1 inch and 24 inch diameters are machined to an accuracy of a few microns and are nitride hardened.

Only V and I standard Johnson-Cousins filters were employed for this study as other filters were found to have deteriorated by environmental effects so their data were not considered.

Technical specifications of the MKBU telescope with ST-7XME CCD camera and focal reducer used are listed in Table 1[17].

[14] *https://www.google.com/maps/place/Bhavnagar+Observatory/@21.7543468,72.1303431,19z/data=!4m5!3m4!1s0x0:0x30504b9860ad6057!8m2!3d21.7542085!4d72.1303511?hl=en*

[15] *https://en.wikipedia.org/wiki/Photometric_system*

[16] *https://www.iucaa.in/*

[17] *https://www.qdigital-astro.com/calculator*

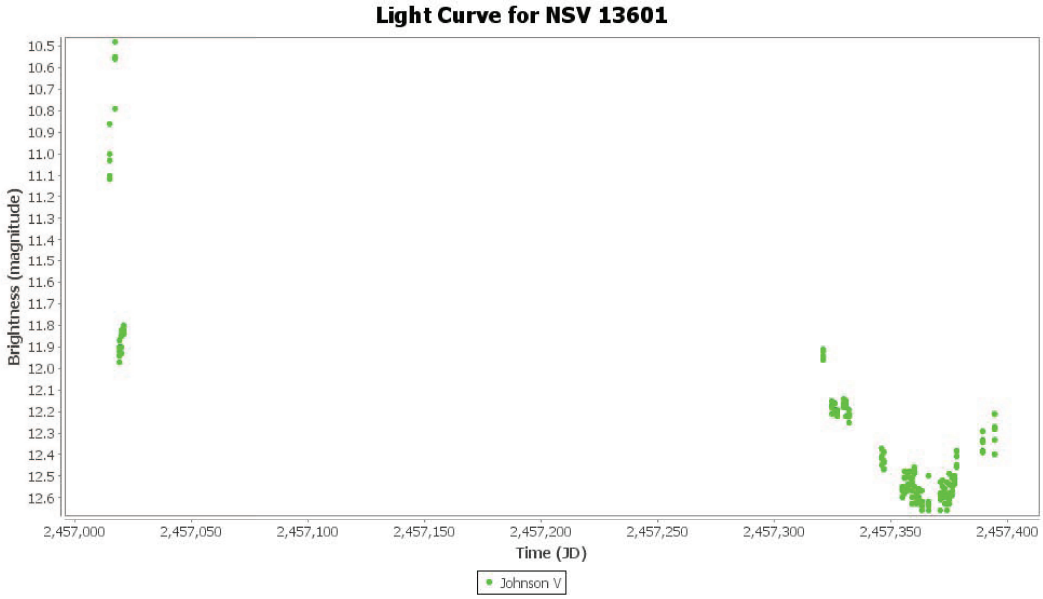

Fig. 2 LC of NSV 13601 (MKBU Data-V).

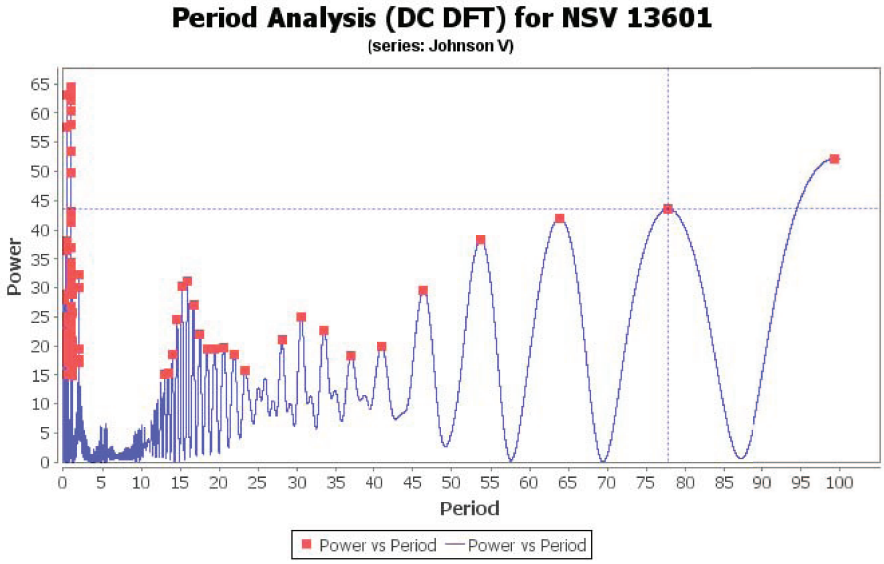

Fig. 3 DC-DFT Periodogram of NSV 13601.

2.2 Observations and Data Reduction

MaxIm DL photometric image analysis software was employed for our data reduction work. All time-series astronomical images were first calibrated for basic noise removal and then all continuous sequences were aligned and photometry performed on them.

For flat fielding, twilight images of sky were captured and used daily. After all the images were captured, master files were generated for each of these and applied for the final calibration part.

In MaxIm DL, all the flats, darks and bias files were combined into a single standard master file according to different photometry filters. For calibration, these master files were utilized. The process involved using the object star's light image and calibrating the master calibration files in MaxIm DL. This way, all the light data images were calibrated for each observation. Subsequently, these calibrated light images were aligned with the alignment tool of the MaxIm DL. These aligned images were integrated to get better signal-to-noise ratio.

These calibrated and integrated light images were applied in the differential photometry tool of MaxIm DL, by selecting each individual object star, reference star and check stars. By providing proper inputs to the MaxIm DL, this results in a magnitude vs Julian day (JD) graph in CSV

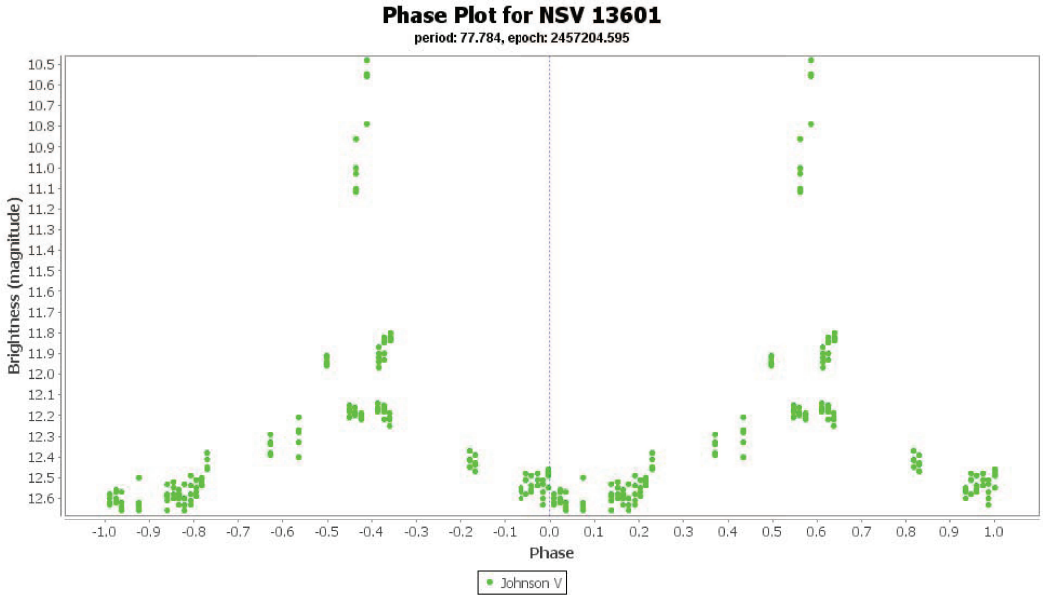

Fig. 4 PLC of NSV 13601.

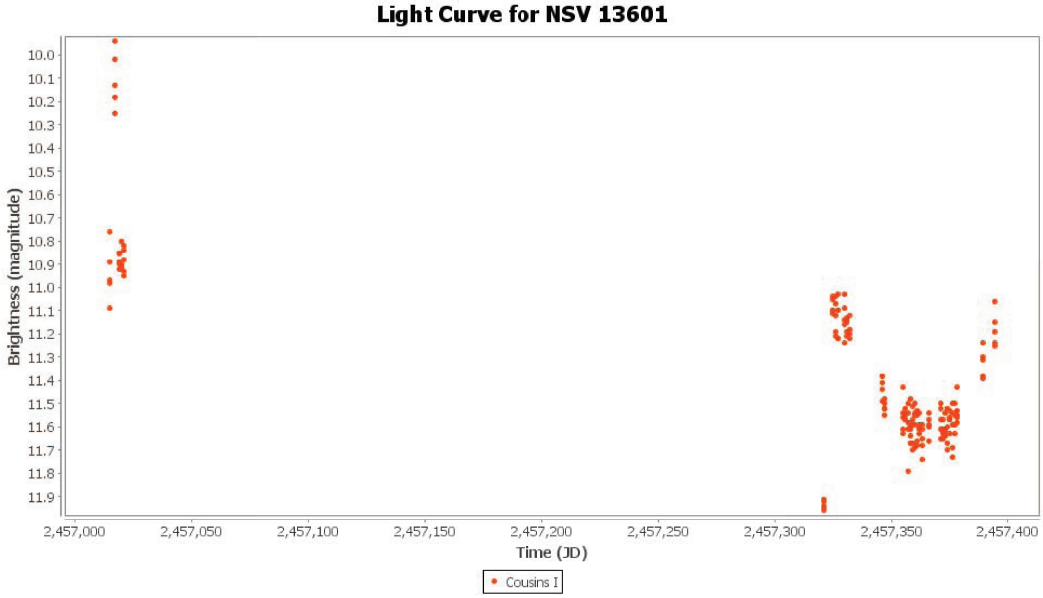

Fig. 5 LC of NSV 13601 (MKBU Data-Ic).

or AAVSO text format file. The time accuracy is as good as what can be achieved by GPS time syncing.

An object star, one check star (standard star) and one comparison star were identified to perform differential photometry (Rodriguez-Gil & Torres 2005). Standard observatory procedures were followed with minimum airmass considerations.

For data reduction (calibration), flats field frames, dark frames and bias frames as well as light frames were set in the MaxIm DL configuration, which then collects each of these automatically according to set exposure time and other Johnson-Cousins $UBVRI$ filter value settings. All the LC analysis was performed in VStar, and to double check the results, Period04 (a standard astronomy time-series analysis package) was also employed.

Aladin[18] was used to compare the captured CCD image with the standard field image.

2.2.1 *Differential photometry*

For standardization of CCD photometric method and to calibrate the whole system, five known variable stars were studied, one of which was presented in Gohil and

[18] `https://aladin.u-strasbg.fr/`

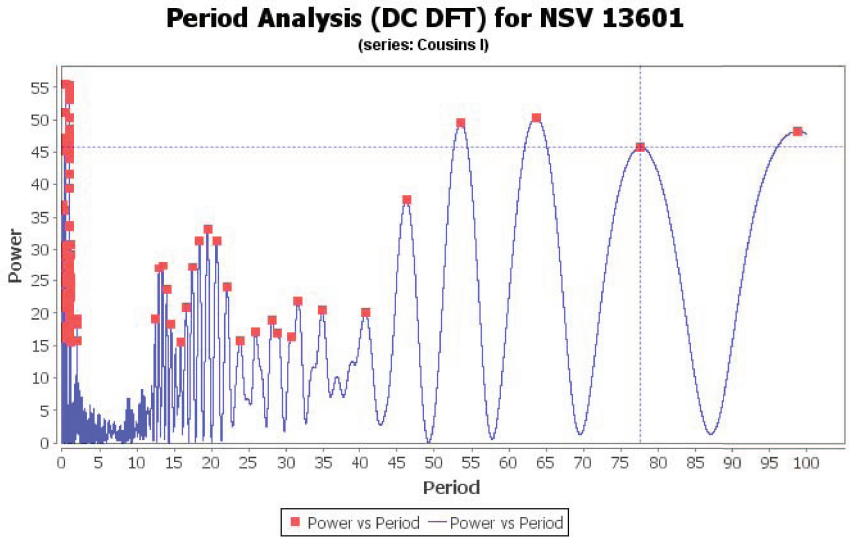

Fig. 6 DC-DFT Periodogram of NSV 13601.

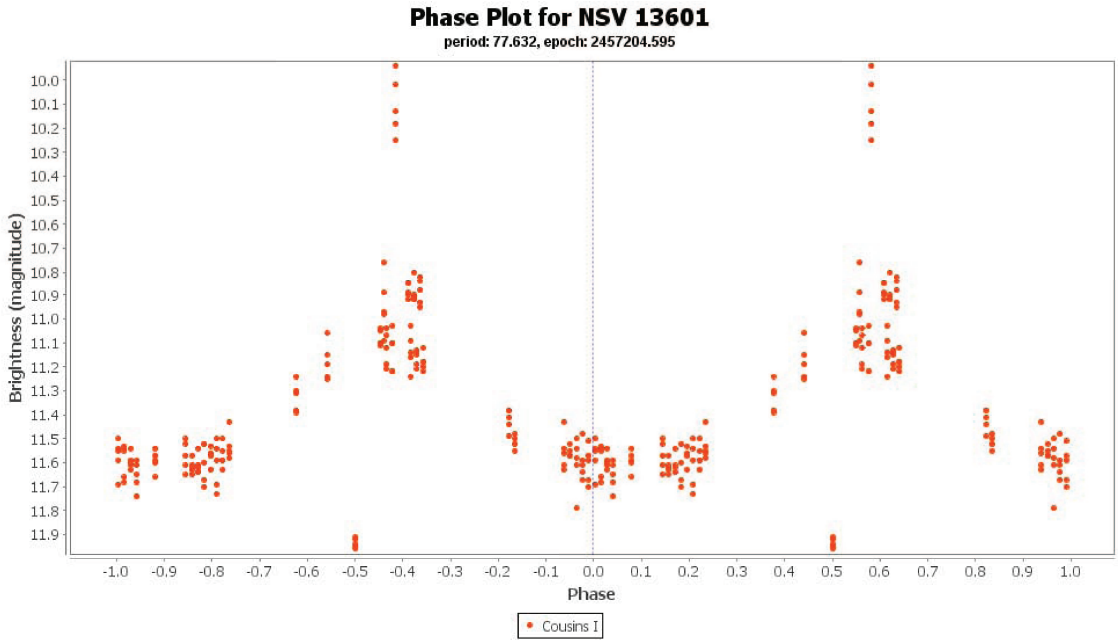

Fig. 7 PLC of NSV 13601.

Bhatnagar (2019). This section discusses the basic CCD differential photometry performed on suspected variable NSV 13601.

For finding the suspected variable star, GCVS[19] and VSX[2] databases were referenced. NSV 13601, a suspected variable star, was shortlisted based on its closeness to zenith at the observation location and time. NSV 13601 was selected due to its magnitude being less than 15, suitable for observing from a small telescope located in a semi-urban area.

All the flats (flat CCD image frames) were also acquired in different filters daily at dusk when the sky was evenly lit. The CCD's internal Peltier cooler was kept at its minimum temperature (around –20°C) during all the observations to reduce thermal noise.

The target observation photometric sequences followed were optimum for differential photometry (Miles 1998J). The sequence of observation was

Bias –>Dark –> "Object Star + Comparison Star + Check Star" –>Dark –>Bias (for each filter).

The step "Object Star + Comparison Star + Check Star" was carried out so that they were near each other and could be located in the same CCD image frame.

[19] `http://www.sai.msu.su/gcvs/gcvs/`

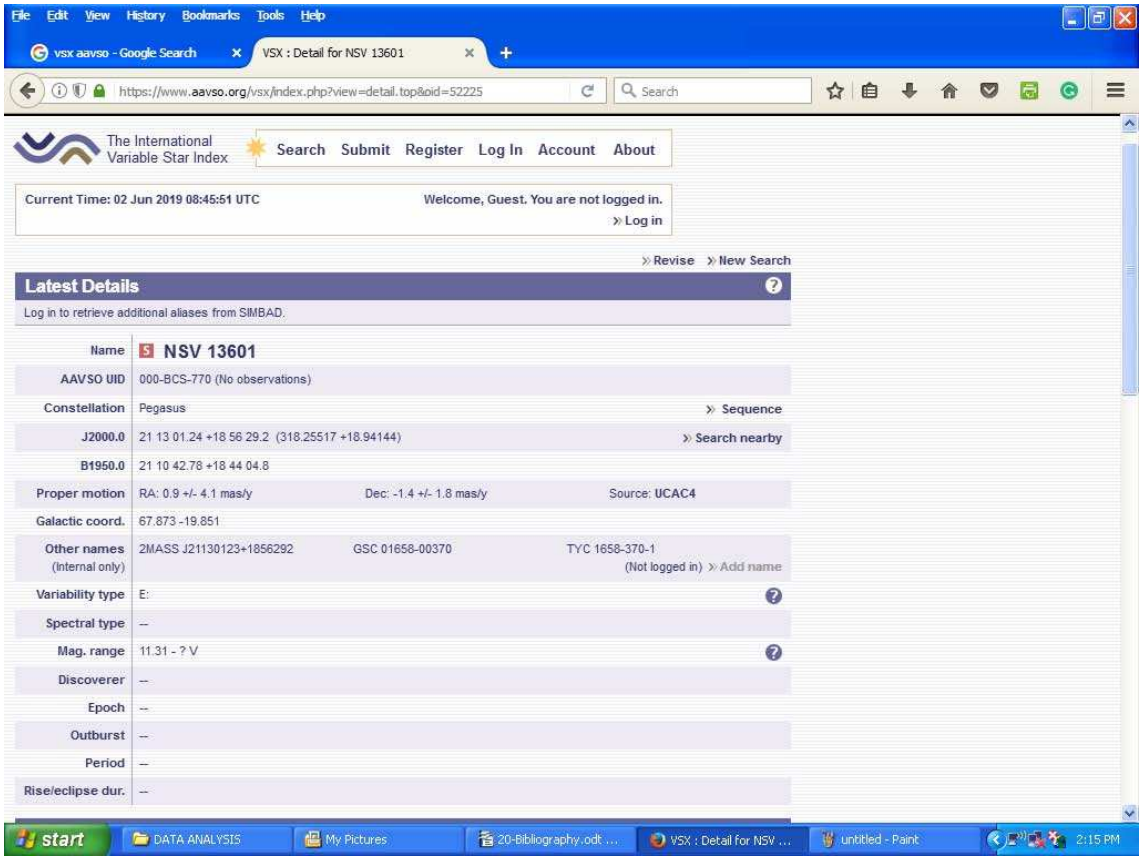

Fig. 8 Recent screenshots of NSV 13601 on VSX, still classified as a suspected variable.

For aperture photometry, the aperture, annulus and gap were chosen so that the aperture only contained the star's light and the annulus contained the background.

From the images thus acquired, the intensity was differentially derived by the Photometry tool of MaxIm DL[20] for the target using the known comparison and standard stars. The LCs were obtained for the target star from each combined CCD image generated at different times.

Only data from V and Ic photometric filters were considered as the data from other filters were found to be unreliable due to their environmental deterioration. The standard extinction correction could not be carried out in the conventional photometric way. Therefore for atmospheric corrections, it became advantageous to observe only when the object star, comparison star and check star were at the zenith. The CCD differential photometry takes care of the corrections. Moonless clear (photometric) nights were selected for observations.

The data labeled as MKBU were recorded at MKBU's observatory[21].

Suspected Variable Stars

The data presented here were captured at the beginning of this study (∼2014). Since then, some additional information on variability has become available. Details are given for NSV 13601.

2.2.2 Time-series analysis

Time-series analysis on the data collected at MKBU observatory[21] and the results derived are presented in this section. This time-series analysis was mainly done in VStar (AAVSO) software[22]. LCs were generated by MaxIm DL[20] and directly applied as input into VStar software. Time-series analysis was performed to find periods of NSV 13601. Initially, the constellation Gemini was studied to test and calibrate data captured as well as the analysis method. Satisfactory results were generated by analyzing these stars. Then, the time-series analysis was performed on NSV 13601.

First, the LCs were inspected on different time scales in VStar to roughly find the daily variation of the object star. Then the detailed time-series analysis, using the Date Compensated Discreet Fourier Transform (DC-DFT) facility of VStar, was carried out on the MKBU data. It gave the top frequency hits, which were probable candidates for

[20] `https://diffractionlimited.com/`
[21] `https://mkbhavuni.edu.in/mkbhavuniweb/`
[22] `http://www.citizensky.org/content/vstar`

Table 2 Object, Check and Comparison Star Table: (NSV 13601)

Star type	AUID	J2000.0		Magnitudes				
		(RA)	(DEC)	(B)	(V)	$(B-V)$	(Rc)	(Ic)
Object Star	000-BCS-770	21:13:01.24	18:56:29.20	-	11.31 – ?	-	-	-
Check Star	000-BCS-776	21:13:11.29	18:57:12.1	11.665 (0.155)*	11.386 (0.026)$^\#$	0.279 (0.157)	-	10.833 (0.143)$^\$$
Comparison Star-1	000-BCS-777	21:13:13.29	18:58:03.7	-	11.875 (0.137)$^\$$	-	-	11.144 (0.217)$^\$$
Comparison Star-2	000-BCS-764	21:12:37.32	19:02:54.9	12.478 (0.257)*	11.044 (0.023)$^\#$	1.434 (0.258)	-	9.667 (0.126)$^\$$

Notes: Here, $\star$ = Tycho-2, \$ = TASS, $\#$ = ASAS3.

Table 3 Time-series Analysis Results of NSV 13601

Star Name (NSV 13601)	MKBU Data (V) (d)	MKBU Data (Ic) (d)
VStar	77.784	77.632
Period04	77.058	49.560

the object star's period. The periodogram and power spectrum were generated and after selecting the most probable frequency for the period of the variable star, and phased light curve (PLCs) were drawn. The PLCs and residual spectrum were model fit, and the mean fit curve was also drawn. This sequence was carried out on all data collected at MKBU for variable and suspected variable stars.

In the following sections, the respective graphs, figures and tables are provided for each star and in the end their period search results are also listed in respective tables. The Period04 software package[23] was also employed to verify the results, (Period04 is very well known for searching frequency of time-series data using Fourier transform). Accurate results provided by Period04 were also compared with results of VStar with their respective photometric filters and then the frequencies which were common in all the results were selected.

For NSV 13601, scattered data were available from a few sources. The observations at MKBU have produced new data for these suspected variables. Already, massive efforts are ongoing to gather and process data from various sources automatically and update the status.

Presentation of Analyzed data:

The following sections present analysis of time-series data from the MKBU telescope as well as from other sources (where available) for NSV 13601 using VStar. Each presented analysis graphically contains several results from various steps describing either data sufficiency or are checkpoints in analysis. Descriptions given below are for NSV 13601 (Figs. 2 to 7). The sequence of analyzed data presented is by VStar only. We included Period04's analysis result directly in Table 3 for the purpose of comparison. This sequence is followed by data from the MKBU telescope (for both V and Ic filters). Finally, the conclusions drawn are presented.

[23] `http://www.univie.ac.at/tops/Period04/`

Figure 2 displays the LC of NSV 13601, which is the Johnson V mag vs JD graph. LC graph depicts Cousins Ic mag vs JD only for the MKBU Data-Ic filter. However, for all other data, the Johnson V filter mag vs JD graph is plotted.

In the time-series, DC-DFT was applied and as a result, top-frequency hits were found along with the periodogram (Fig. 3) and power spectrum.

Frequency with highest amplitude was selected as the most probable frequency of the variable star and PLC (Fig. 4) was drawn. By looking at the PLC, it can be reasonably inferred whether the star is a variable or not.

Table 3 lists the results of the pre-whitening process, in which every possible frequency is extracted and then that frequency is removed from the remaining data and again Fourier transform is applied on residuals. This process is followed till the residual value reaches near 0.01. After that, it is assured that no other possible frequency of a variable star is left in the data anymore.

Sometimes when time-series data did not perform/pass these checks as they should, Period04's frequency analysis and VStar's Top frequency hits were compared and the most common frequency was selected for the period.

Time-Series Analysis of Suspected Variable Star NSV 13601:

VStar Analysis: (MKBU Data)

1. Visual Filter (V):

From Figures 2 to 4, LC, DC-DFT periodogram and PLC are displayed respectively for MKBU data in V filter.

2. Infrared Filter (Ic):

From Figures 5 to 7, LC, DC-DFT periodogram and PLC are exhibited respectively for MKBU data in Ic filter.

3 RESULTS

Many of the known variable stars were examined for calibration of MKBUs photometric system and method. Many suspected variable stars were shortlisted and considered by staff at the MKBU telescope. Here, their results are presented. Their period as well as their magnitude were determined. Presented below are the summarized results of the analysis of the selected stars.

4 CONCLUSIONS

NSV 13601 is a variable star. Some more study is required to define its variability more precisely.

Our aim and strategy were to first standardize our photometric system and then search for suspected variables, which may be short-period, and conduct the associated time-series analysis. As a result of our study, we derived all of our suspected variable star's periods and magnitude to a scientifically satisfactory level.

At the time of our selection ($\sim$2014) for NSV 13601, it was classified as a suspected variable on VSX, CDS and other astronomical databases.

Recently (2019 May 15) it was found that some databases (mainly CDS) have been updated and are now listing some earlier suspected stars as variable stars. VSX is still reporting them as suspected as before (as on 2019 June 1) (sample screen shot in Fig. 8).

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