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Characterization of eclipsing binaries in High Latitude Field 356

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ABSTRACT

Variable stars in HLF 356 identified from plates taken at Harvard Observatory southern station in the 1930s are characterised using data from the ASAS, SuperWASP and Catalina Sky Survey databases. Very little work has been done on these variables since their discovery. Their periods are determined, and light curves for these stars are presented, from which their classification is determined.

1. Introduction

Automated sky surveys have ushered in a new era in Astronomy, from discovering thousands of variable stars to providing much needed data for known stars. It is estimated that millions of variable stars will be observed and detected by the ESA Gaia and LSST projects (Eyer et al., 2012). Dealing with large numbers such as these requires automated classification routines and efficient machine-learning techniques. The success of these automated routines requires a learning set of known variables with established light curves, correct variable type classifications and accurate ephemerides. However, there are many variables listed in catalogues for which very little or no further follow-up observations have been performed since their discovery. Several of the variables identified in High Latitude Field (HLF) 356 are an example of this.

HLF 356 is a 10° × 10° area of the sky centred on

$$\alpha_{1900} = 12^h\,40^m \quad \equiv \quad \alpha_{J2000} = 12^h\,45^m\,23^s$$

$$\delta_{1900} = -32°00' \quad \equiv \quad \delta_{J2000} = -32°02'50''$$

with old galactic coordinates $l^I = 270°$ and $b^I = +31°$. Covering about 80 square degrees, HLF 356 lies above the Galactic plane and spans a region lying in the constellations of Centaurus and Hydra. There are no obvious open or globular clusters nor any emission, reflection, dark or planetary nebulae in the field.

Between 1935 March and 1938 July, 102 photographic plates were taken of HLF 356 using a 10″ telescope and 14 plates using a 24″ telescope at the Harvard Observatory southern station in Arequipa, Peru. The stars on these plates have photographic magnitudes in the range $11.0 \le V_{pg} \le 16.5$, with many of them falling in the range 12–14 mag. HLF 356 turned out to be rich in variable stars. Huruhata (1940) (hereafter H40) identified 108 variables in the field and a further 18 stars that had variations with amplitudes less than 0.5 mag which he listed as suspected variables.

All variables were classified by H40 as cluster, eclipsing, short, long, irregular or SS Cyg types and were given Harvard Variable (HV) numbers. Eclipsing and irregular are categories that are still in use today, while cluster, short, long and SS Cyg-types are now broadly categorized as RR Lyrae (hereafter RR, with subcategories RRab and RRc), δ Scuti, Mira and dwarf nova respectively. We use the term cataclysmic variable (CV) for the SS Cyg-type stars. All of these broad categories have many subcategories. If V_{max}, V_{min} and an approximate period were determined, the stars were included in the first edition of the General Catalogue of Variable Stars (GCVS1[1]) (Kukarkin and Parenago, 1948). Many of the other variable stars are listed in the New Suspected Variable (NSV) catalogue or have been identified in recent surveys and appear in GCVS4 with variable star designations. For example, Otero (2003), Otero and Wils (2005) and Otero et al. (2006) combined data from the All Sky Automated Survey (ASAS) (Pojmanski, 2002), *Hipparcos* (Perryman et al., 1997) and the Northern Sky Variability Survey (NSVS) (Woźniak et al., 2004) to determine ephemerides and classifications for several of the stars. Many (but not all) of the variables in HLF 356 have been identified and classified by Drake et al. (2017) using data from the Catalina Survey. However, there are still instances where the classifications are uncertain, light curves have not been published, and accurate periods and period rates of change have not been determined. There are a few stars whose published coordinates are incorrect.

The 18 suspected variables identified by H40 were not given HV numbers. All of these stars were put in the NSV catalogue, but some have subsequently been given GCVS names. We use the designations

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[1] GCVSn refers to the nth edition of the catalogue.

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S1–S18 to identify these stars, based on their order in H40's Table II, together with their GCVS or NSV identification.

We have used data from the Wide Angle Search for Planets (WASP), the ASAS and the Catalina Sky Survey (CSS) to determine ephemerides and classifications for the H40 sample. In Section 2 we discuss the different surveys and in Section 3 the methods used to analyse the respective data sets are discussed. In Section 4 results of the analysis are presented together with phase-magnitude diagrams (hereafter PMDs) and descriptions of interesting features in the light curves. In an Appendix we present PMDs of all the data that are not included in the main text.

2. Data sources

The WASP project was established to search for photometric variations in stars caused by transits of exoplanets. The WASP field-of-view (FoV) is 7.8° × 7.8°, giving a resolution of 13.7 arcsec pixel^{-1}. Broadband filters with a passband from 400 to 700 nm provide uniform spectral coverage on all instruments (Pollacco et al., 2006). The nominal magnitude range covered by WASP is $V \approx 9.0 - 13.5$, but data for sources fainter than 16 mag are available. The WASP data reported here were collected by the WASP southern station located at the South African Astronomical Observatory in Sutherland.

The WASP observing strategy is to cycle through several fields of similar declination separated by roughly 1 h in right ascension, but avoiding crowded fields close to the Galactic plane. Two 30 s exposures are taken of a field before slewing to the next field. This results in each field being sampled every 9–12 min. The data, which includes calibration frames, are processed using a custom-built pipeline (Kane et al., 2004) that performs aperture photometry of the images to produce a flux measurement labelled FLUX2. Systematic errors in the FLUX2 data are removed using a coarse decorrelation technique, followed by application of the SysRem algorithm of Tamuz et al. (2005), generating detrended data labelled TAMFLUX2. Unless stated otherwise, TAMFLUX2 data have been used in the analyses presented here. Because of its wide FoV and observing strategy, the WASP programme collects a large number of photometric data points, making it a valuable resource for variability studies.

The ASAS is a project aimed at detecting and monitoring the variability of stars with magnitudes in the range $8 \lesssim V \lesssim 14$. The ASAS-3 system (Pojmanski, 2002) provides a FoV of 8.5° × 8.5° with a resolution of 14.8 arcsec pixel^{-1} and is equipped with standard Johnson V-band filters. A 180 s exposure is taken of each field with the result that the whole visible sky is observed every one to three nights. For our southern field, we have used data from the Las Campanas Observatory of ASAS.

The ASAS data are calibrated using a pipeline, and simultaneous photometry through five apertures ranging in size from two to six pixels is carried out. Based on the uncertainties in the data, ASAS indicate which aperture is most appropriate to use for each star. We have used the data from their recommended aperture for all our investigations. Data for bright stars can be found in the ASAS Catalogue of Variable Stars (ACVS), whereas data for fainter ones are only available in the ASAS All Stars Catalogue (AASC). ASAS independently estimates a period for the variable stars in the ACVS and suggests classifications based on the shape and period of the folded light curves. The stars in the AASC have no determined parameters.

The CSS was established to search for near-Earth objects and potential hazardous asteroids (Larson et al., 2003). The CSS has a smaller FoV, 4° × 4°, and resolution, 3.5 arcsec pixel^{-1}, compared to both WASP and ASAS. Unfiltered observations are taken in sets of four images separated by 10 mins with typical exposure times of 30 s. V magnitudes are obtained by transforming from 2MASS JHK colours using a set of equations determined from a sample of G0–G8 dwarf stars. For the southern hemisphere observations reported here, data collected at Siding Spring, Australia (SSS) have been used. The magnitude limits of SSS are $11 < V < 19$ mag making it a useful source of photometric data for targets fainter than those found in WASP and ASAS. The higher resolution of CSS/SSS means that there is less contamination from nearby stars.

3. Data analysis

The WASP, ASAS and CSS data all consist of a measurement of time from the mid-point of the observations, a magnitude or flux measurement and an associated uncertainty. The measurements produce a time series of data containing gaps and noise. By folding the data on the orbital or spin period of the system, a PMD is created with the phase of a complete cycle running from 0 to 1. The resulting PMD greatly simplifies the process of removing bad data from the time series.

Although the online data repositories for the three surveys provide periods for the stars, we have determined a period on which to fold the data independently. The programme Period04 (Lenz and Breger, 2005)[2] (hereafter P04) was used to determine an initial folding period. A standard pre-whitening iterative procedure was used over the whole data set to determine its Fourier components. The method consists of fitting a sinusoid to the data, subtracting this optimized fit and then computing a peak in the residuals. For a time-series $g(t)$, P04 uses a fitting formula given by

$$g(t) = Z + \Sigma_i A_i \sin(2\pi(f_i t + \Phi_i)) , \quad (1)$$

where Z is the zero-point shift, A_i are the amplitudes of each component, f_i their frequencies, and Φ_i their phases. The time t that we used was t = HJD − 245, 0000; times of this form are represented by HJD xxxx. The computations were terminated when the frequency of a peak did not correspond to an harmonic of the fundamental period $P = 1/f_1$ (i.e. $f_i \neq nf_1$ for $n = 1, 2, 3, \cdots$).

3.1. WASP data

Most of the data sets cover a time period from HJD 3860 (2006 May 04) to HJD 6107 (2012 June 28), and have data for five seasons (2006, 2007, 2008, 2011 and 2012). For many of the stars in the HLF 356 field there are over 20,000 points per source in the WASP database.

The quality of the data displays significant variations. There are certain nights where the data are totally uncorrelated, and times when part of the evening can be very stable so that a clear light curve is present, but at other times the data points are scattered. Data from these periods have been discarded. To clean the data, the first step involved looking at the complete time-series and truncating it at an upper and lower value, as illustrated in Fig. 1. The cleaning programme then presented three windows showing the folded data for a season, the time-series of the season, and the data for one night; the single night of data is shown in red dots on the other two plots. Individual points or sections of the data can be discarded by interacting with the third window. Examples of the windows are shown in Fig. 2.

The cleaned data were then subjected to an O–C analysis to refine the period and determine, or set limits on, changes in the period. The process consisted of going through the data and selecting minima that had several points lying within a phase of ± 0.04 of the minimum. A parabola was fitted to each minimum by least squares, and the time of minimum, t_{min}, and its uncertainty, σ_t, determined. The times of minimum were used in an O–C analysis and fitted to an ephemeris of the form

$$\mathrm{HJD} = T_0 + P^*E + a^*E^2$$

to determine the epoch of minimum brightness T_0, the period P, and a, along with their corresponding uncertainties. The coefficient a is related to the period rate of change by

[2] Available from http://www.univie.ac.at/tops/Period04/.