Search for Evolutionary Changes in Cepheid Periods Using the Harvard Plate Collection: RS Puppis

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Received October 27, 2008

Abstract—Based on photographic plates from the Harvard College Observatory, we have made 1492 magnitude estimates for the long-period classical Cepheid RS Pup ($P = 41.4$ d). Together with the observations taken from the literature, our data have allowed us to construct an $O-C$ diagram spanning a time interval of 135 years. The $O-C$ diagram has the shape of a parabola, which has made it possible to determine for the first time the quadratic light elements and to calculate the rate of evolutionary increase in the period, $\dot{P} = 119.3 (\pm 3.0)$ s yr$^{-1}$, in agreement with the results of theoretical calculations for the third crossing of the instability strip. The available data reduced by the method of Eddington and Plakidis (1929) have revealed random fluctuations in the period of $\sim 0.225$ d. However, they do not dominate on the $O-C$ diagram, because the progressive evolutionary changes in the period in a 135-year interval lead to an amplitude of the evolutionary changes in the $O-C$ residuals that exceeds the amplitude of the random fluctuations in the $O-C$ residuals by a factor of 3.

PACS numbers: 97.60.-s; 97.30.-b
DO: 10.1134/S1063773709060061

Key words: Cepheids, period variability, stellar evolution.

INTRODUCTION

According to theoretical calculations, the evolutionary changes in the periods of even short-period Cepheids ($P \sim 6$ d) become easily detectable over an observing time of the order of a century (Fernie 1990; Berdnikov et al. 2000). Since longer-period (and, hence, higher-mass) Cepheids evolve faster, the progressive changes in the periods of the longest-period Cepheids ($P > 30$ d) will be detectable even in a time interval of only a few decades.

We studied the pulsation stability in a time interval of more than a century for six long-period Cepheids: EV Aql ($P = 38.7$ d) (Berdnikov 1994), NSV 9159 ($P = 38.9$ d) (Berdnikov et al. 2009), SV Vul ($P = 45.1$ d) (Berdnikov 1994), GY Sge ($P = 51.5$ d) (Berdnikov et al. 2007), V1496 Aql ($P = 65.4$ d) (Berdnikov et al. 2004), and S Vul ($P = 68.0$ d) (Berdnikov 1994). The $O-C$ diagrams turned out to have a distinct parabolic shape only for three of them (NSV 9159, S Vul, and SV Vul). The $O-C$ diagrams for GY Sge and V1496 Aql are dominated by irregular fluctuations in the $O-C$ residuals attributable to random fluctuations in pulsation periods; as regards EV Aql, the available data are still insufficient for firm conclusions to be reached.

Analysis of all the available data showed that on the whole, as the theory predicts, the $O-C$ diagrams for almost 90% of the Cepheids reveal evidence of evolutionary changes in periods when the observing time interval approaches a century. Therefore, the fact that the periods for half of the investigated long-period Cepheids do not exhibit the above-mentioned changes is puzzling. The statistics must be increased to understand the cause of such a behavior. Therefore, we included all Cepheids with periods of more than 30 d in the program of our studies. In this paper, we present the results of studying the period variability for RS Pup ($P = 41.4$).
Table 1. Observational material for RS Pup

<table>
<thead>
<tr>
<th>Data source</th>
<th>Number of measurements</th>
<th>Type of observations</th>
<th>JD interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvard</td>
<td>1492</td>
<td>Photographic (PG)</td>
<td>2411491–2447683</td>
</tr>
<tr>
<td>AAVSO</td>
<td>1988</td>
<td>Visual (VIS)</td>
<td>2414962–2453786</td>
</tr>
<tr>
<td>AAVSO</td>
<td>215</td>
<td>CCD (B, V)</td>
<td>2453804–2454605</td>
</tr>
<tr>
<td>ASAS-3</td>
<td>514</td>
<td>CCD (V)</td>
<td>2451185–2454606</td>
</tr>
<tr>
<td>Literature</td>
<td>1272</td>
<td>Photoelectric (B, V)</td>
<td>2433765–2453118</td>
</tr>
<tr>
<td>Literature</td>
<td>138</td>
<td>Photographic (PG)</td>
<td>2410649–2436277</td>
</tr>
<tr>
<td>Literature</td>
<td>137</td>
<td>Visual (VIS)</td>
<td>2405173–2453786</td>
</tr>
</tbody>
</table>

THE TECHNIQUE AND OBSERVATION MATERIAL

To study the Cepheid period variability, we use the universally accepted technique of analyzing the $O-C$ diagrams; the most accurate method for determining the $O-C$ residuals is the method of Hertzsprung (1919), whose computer implementation was described by Berdnikov (1992). To confirm the reality of the detected period changes, it should be shown that the random fluctuations in the pulsation period, if present, are not dominant on the $O-C$ diagram; we search for these random fluctuations using the technique described by Eddington and Plakidis (1929).

The variability of RS Pup was discovered on seven photographic plates (Gill 1893) taken in 1888–1890 to compile the CPD catalog. Subsequently, it turned out that the magnitude of this bright variable was measured visually seven times in 1873–1891 by the compilers of the CoD catalog. All these photographic and visual observations are given in Innes (1902), which allowed the earliest times of maximum light to be determined for RS Pup.

To construct the $O-C$ diagram for the Cepheid RS Pup, we used the times of its maximum light determined from 1482 photographic observations that we obtained in the plate collections of the Harvard College University and from visual and CCD observations available in the International Database of the American Association of Variable Star Observers (AAVSO) and the ASAS-3 catalog (Pojmanski 2002). In addition, we used published visual, photographic, and photoelectric observations. Brief information about all of the observations used is presented in Table 1.

The oldest visual magnitude estimate for RS Pup was made in 1873 and the latest CCD image was obtained in 2008. Consequently, our data span a time interval of 135 years.

RESULTS AND DISCUSSION

The results of our reduction of the seasonal light curves for RS Pup are presented in Table 2.1

Columns 1 and 2 give the times of maximum light and their errors; column 3 gives the type of observations (see Table 1); columns 4 and 5 contain the epoch number $E$ and the $O-C$ residual; columns 6 and 7 contain the number of observations $N$ and the data source. The $O-C$ residuals from Table 2 are indicated in Fig. 1 by the squares for our Harvard photographic magnitude estimates, the triangles for the observations from the AAVSO International database, and the circles for the published observations; the vertical bars indicate the limits of the errors in the $O-C$ residuals. The $O-C$ residuals in Fig. 1 are expressed in fractions of the period.

The period of RS Pup was studied by Gerasimovič (1927), Voûte (1937), and Parenago (1956). However, since the then available data spanned a short time interval, no slow progressive changes in the period were detected against the background of its random fluctuations. Our data span a much longer time interval and the existing random period fluctuations are no longer able to wash away the parabolic shape of the $O-C$ diagram in Fig 1a. This allows the quadratic light elements to be obtained for the first time:

1Table 2 is published entirely in electronic form only and is accessible via http://vizier.u-strasbg.fr/cats/J.PAZh.htx. Nevertheless, the list of references contains all primary sources from the seventh table.