COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS

Number 4362

Konkoly Observatory
Budapest
5 August 1996

HU ISSN 0374 – 0676

ECCENTRIC ECLIPSING BINARY STARS AS TEST OF GENERAL RELATIVITY: THE CASE OF V541 CYGNI

V541 Cyg (BD+30°3704; V_{max} = +10.35; B−V = +0.035) is a detached eclipsing binary consisting of a pair of B9.5 V stars having an eccentric orbit (e = 0.474) and an orbital period of P_{orb} = 15.34 days. Khaliullin (1983; 1985) was the first to show that this binary could be an important test case for General Relativity (GR) because the apsidal motion expected from GR is significantly larger than the classical apsidal motion arising from the tidal and rotational distortions of the component stars. He found that the rate of apsidal motion expected from GR is $\dot\omega_{GR} = 0\overset{\circ}{.}82/100\mathrm{yr}$, while the contribution to apsidal motion from classical effects is $\dot\omega_{cl} = 0\overset{\circ}{.}15/100\mathrm{yr}$. Moreover, the relativistic apsidal motion expected for V541 Cyg is large — about 70 times greater than the corresponding relativistic apsidal motion of Mercury-Sun of $\dot\omega_{GR} = 43''/100\mathrm{yr}$.

From the data available at that time, Khaliullin (1985) found good agreement between the observed apsidal motion rate of V541 Cyg of $\dot\omega_{obs} = 0\overset{\circ}{.}90/100\mathrm{yr} \pm 0\overset{\circ}{.}15/100\mathrm{yr}$ and the theoretical combined relativistic and classical apsidal motion of $\dot\omega_{GR+cl} = 0\overset{\circ}{.}97/100\mathrm{yr}$. However, this determination of apsidal motion was based on only two epochs: very accurate eclipse timings from his photoelectric photometry made in 1981–83 and less accurate photographic minima determinations of Karpowicz (1961), made during 1955–59. Since 1985, several accurate times of primary and secondary minima have been determined from photoelectric or CCD photometry. Recently Wolf (1995) re-determined the apsidal motion using Khaliullin's data as well as more recent eclipse timings and derived a more refined apsidal motion rate of $\dot\omega_{obs} = 0\overset{\circ}{.}53/100\mathrm{yr} \pm 0\overset{\circ}{.}11/100\mathrm{yr}$. However, this revised apsidal motion rate is significantly smaller than expected from theory. Using updated values for the internal structure constant (see Claret and Gimenez 1992), theory predicts relativistic effects of $\dot\omega_{GR} = 0\overset{\circ}{.}77/100\mathrm{yr} \pm 0\overset{\circ}{.}05/100\mathrm{yr}$ and classical effects of $\dot\omega_{cl} = 0\overset{\circ}{.}10/100\mathrm{yr} \pm 0\overset{\circ}{.}02/100\mathrm{yr}$, resulting in a combined apsidal motion rate of $\dot\omega_{GR+cl} = 0\overset{\circ}{.}87/100\mathrm{yr} \pm 0\overset{\circ}{.}07/100\mathrm{yr}$. This result is particularly interesting because in V541 Cyg most of the apsidal motion is expected to arise from GR.

Starting in the Spring of 1995, UBVR photoelectric photometry of V541 Cyg has been conducted on the Villanova-Fairborn 0.8m Automatic Photoelectric Telescope (APT), at Mt. Hopkins, Arizona. During 1995, differential photometry of the star was obtained on 63 photometric nights. Nearly complete light curves have been obtained and new eclipse timings have been made from these data. The photoelectric observations were carried out using the usual observing sequence of sky-comparison-check-variable-comparison-sky and an integration time of 10 seconds. Because of the relative faintness of V541 Cyg, blind-offsets from the position of the comparison star were used to acquire the star. Initially HD 332470 (SAO 68749; m_v = +8.4; K3 III) was used as the primary comparison star and HD 331210 (SAO 68756; m_v = +9.6; G8 III) served as the check star. However, after a few months into the observing program, HD 332170 began to show evidence of small systematic changes in brightness especially in the U and B bandpasses.

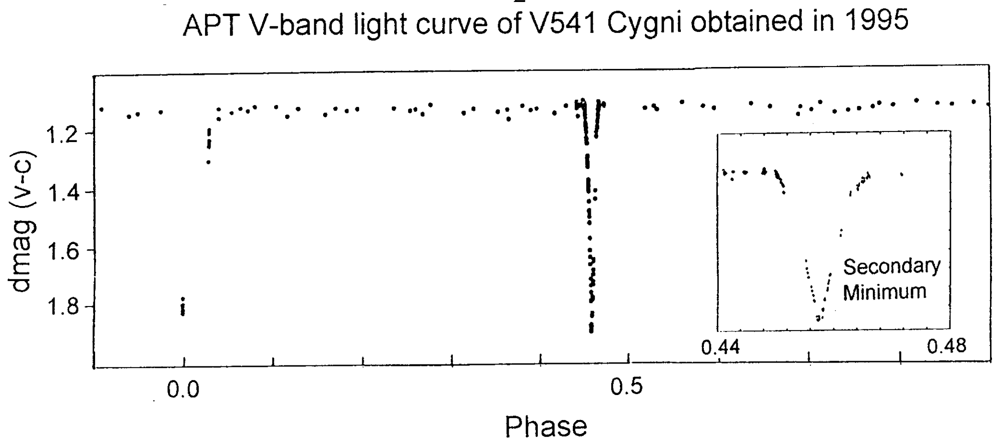

Figure 1. A plot of the the V-band light curve showing the secondary minimum in an expanded phase scale

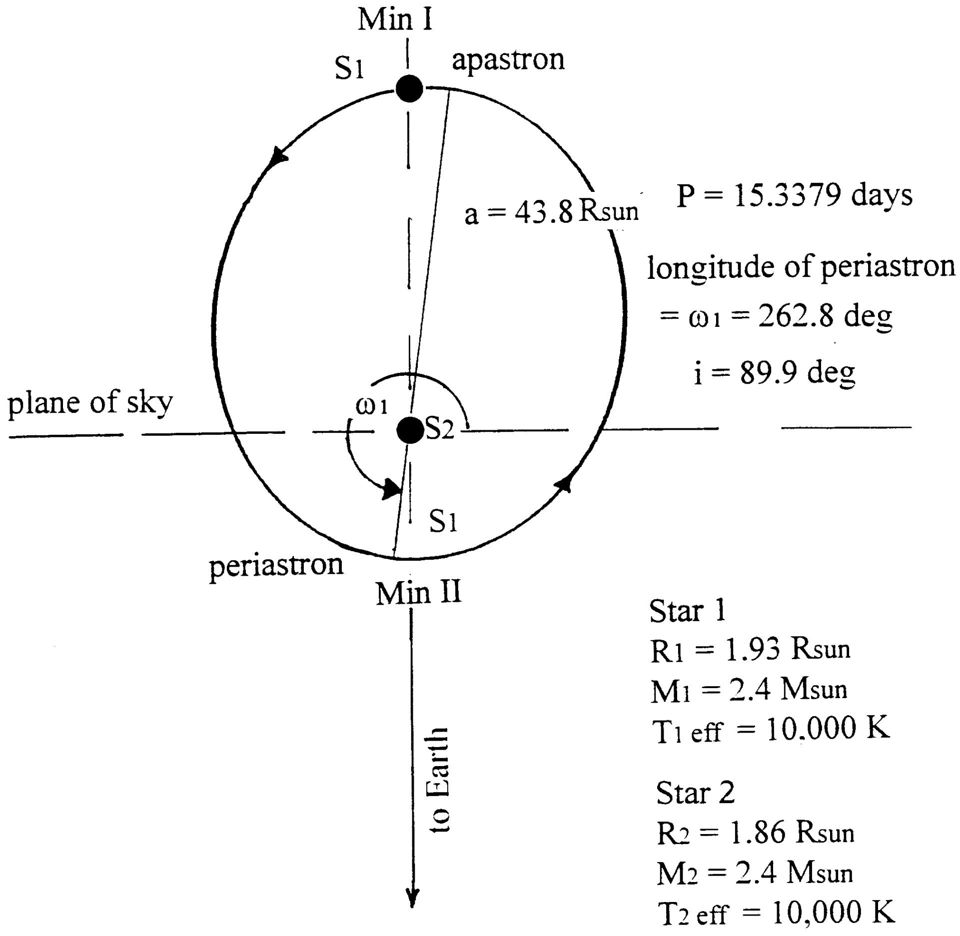

Figure 2. A scale model of the system, showing the orientation of the orbit and the stars drawn to approximate scale

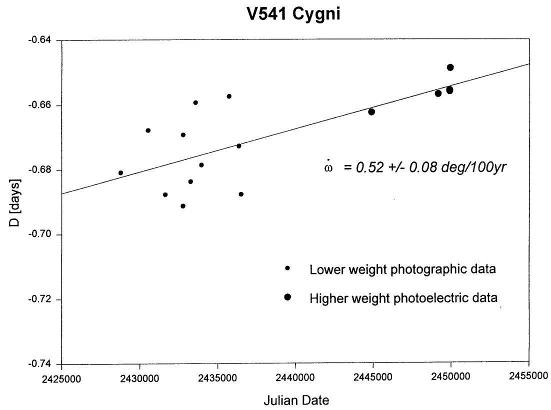

Figure 3. A plot of the apsidal motion rate determination showing the change in the displacement of the secondary eclipse (D $= (t_1 + t_2 - 0.5P)$) with time

Fortunately, frequent observations of the check star were made which enabled us to use HD 331210 as the primary comparison star for the entire 1995 data set. The observations were reduced in the usual way in which times were converted to Heliocentric Julian Day Numbers and the magnitudes were corrected for differential atmospheric extinction. Because of angular proximity of the variable, comparison, and check stars, the differential extinction corrections were very small. Nightly means were formed from the observations outside of the eclipses; typically 3–5 observations comprise each normal point per filter. The observations inside the eclipses were not averaged.

Figure 1 shows the V-band light curve in which the phases were computed from the light elements of Khaliullin (1985); the secondary minimum in an expanded phase scale is also shown in the figure. The eclipses are deep and very narrow; secondary minimum is well defined and occurs near 0.4575 phase, but primary minimum is poorly covered and needs further observations before it is satisfactorily defined. As shown by Khaliullin's photometry, the primary minimum is much broader than the secondary minimum because of the orientation of the orbit ($\omega = 263°$), in which periastron and apastron occur near to the times of the secondary and primary eclipses, respectively. A scale model of the system, showing the orientation of the orbit and the stars drawn to approximate scale is shown in Figure 2.

A very accurate determination of the time of secondary minimum was made from UBVR photometry, obtained near the lower portions of the minimum on the night of 7 July 1995 UT. The time of mid-eclipse was found from least squares fits of the data and by the bisecting cord method. Independent determinations of mid-eclipse were made from the different bandpasses. No systematic differences were found so that a mean timing was calculated from the four data sets:

$$\text{T (Min II)} = \text{HJD}\, 2449904.7145 \pm 0\overset{d}{.}00012$$

A new determination of apsidal motion was made using this timing along with timings given by Khaliullin (1985) and Wolf (1995). In addition to these, the photoelectric and CCD eclipse timings obtained by Lacy and Fox (1992) and Diethelm (1995) were also included. The photographic timings of Karpowicz (1961) were also included, but assigned lower weights than the photoelectric or CCD observations. The analysis of the timings yielded an apsidal motion rate of $\dot{\omega}_{obs} = 0\overset{\circ}{.}52/100\text{yr} \pm 0\overset{\circ}{.}14/100\text{yr}$. This apsidal motion rate is very nearly the same as found by Wolf (1995), which was based on fewer observations. A plot of the apsidal motion rate determination is shown in Figure 3 in which the change in the displacement of the secondary eclipse with time is shown. The older photographic timing estimates were not used in the least squares determination of the apsidal motion, but the apsidal motion found from the modern data fits the older data quite well. More interestingly, this study confirms that V541 Cyg has an observed rate of apsidal motion that is significantly less than the theoretically expected apsidal motion. This smaller than expected apsidal motion found for V541 Cyg is difficult to explain and the discrepancy is in the same sense as found for two other eclipsing binaries, DI Her and AS Cam, in which the relativistic contributions to apsidal motion are also significant (see Guinan and Maloney 1985; Maloney *et al.* 1991; Guinan *et al.* 1994).

Spectroscopic observations of V541 Cyg have been obtained several years ago (by EFG) which indicate approximate stellar masses for the system of about $M_1 = M_2 = 2.4 \pm 0.2 M_\odot$ and projected rotational velocities of the components of $v_1\ sin(i) = v_2\ sin(i) = 20 \pm 5$ km/s. Ultraviolet spectrophotometry (1150 – 3200Å) has also been obtained with the IUE satellite and the preliminary analysis of this data indicates a mean temperature for the two stars of about $T_1 = T_2 = 9900 \pm 400$K. These temperatures correspond to spectral types of about B9.5 V – A0 V. These spectral types and temperatures are in good agreement with the B−V and U−B indices measured recently by Lacy (1992), after the color indices are corrected for interstellar reddening.

We plan to continue photometry of the star with the APT during 1996 to complete the UBVR light curves, in particular, to cover fully the primary eclipse. Also, we are aware that spectroscopic radial velocity observations of V541 Cyg are currently being conducted at San Diego State University by Paul Etzel (priv. commun.). Once the light and radial velocity curves are complete, a more thorough study of this important binary can be made and a more definitive determination of its orbital and physical properties can be obtained.

This study is supported by NSF grants AST-861362 and AST-9315365 which we gratefully acknowledge. The reduction and analysis of the IUE observations were supported by NASA Grant NAG 5-2160.

Edward F. GUINAN
Jamison A. MALEY
James J. MARSHALL
Dept. of Astronomy and Astrophysics
Villanova University
Villanova, PA 19085
U.S.A.

References:

Claret, A. and Gimenez, A., 1992, *Astron. Astrophys. Suppl. Ser.*, **96**, 255
Diethelm, R., 1995, *B.B.S.A.G. Bull.*, 110
Guinan, E.F. and Maloney, F.P., 1985, *Astron. J.*, **90**, 1519
Guinan, E.F., Marshall, J.J., and Maloney, F.P., 1994, *I.B.V.S.*, No. 4101
Karpowicz, M., 1961, *Acta Astr.*, **11**, 51
Khaliullin, Kh.F., 1983, *Astr. Circ. USSR*, **1270**, 1
Khaliullin, Kh.F., 1985, *Ap.J.*, **299**, 688
Lacy, C.H., 1992, *Astron. J.*, **104**, 801
Lacy, C.H.S. and Fox, G.W., 1992, *I.B.V.S.*, No. 4009
Maloney, F.P., Guinan, E.F., and Mukherjee, J., 1991, *Astron. J.*, **102**, 256
Wolf, M., 1995, *I.B.V.S.*, No. 4217