Retrograde Spin-Orbit coupling Effects on the apsidal motion of Eclipsing Binary Star Systems: the case of V541Cygni

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Abstract: It is usually known that the periastra of eclipsing binary star systems precess due to general relativistic effects and classical (Newtonian) tidal and rotational deformations of the stars, whose rotation axes are assumed normal to the orbital plane. For almost all binaries, the expected theoretical and observed apsidal motion rates are in agreement. However, some systems –V541 Cygni, V1143 Cygni, V459 Cassiopeia and AS Camelopardalis – have broken this agreement and resisted explanation for a long time. In this study, we are exclusively dealt with V541 Cygni. We present very tentative theoretical evidence in support of the hypothesis that the retrograde spin-orbit coupling of system causes orbital plane precession in the direction opposite to the relativistic apsidal motion when the spin angular momentum vector is not aligned with the orbital angular momentum vector, thereby reconciling the theoretical and observational results.

Keywords: Eclipsing binary star systems; apsidal motion rate; retrograde spin-orbit coupling precession; V541 Cygni.

1. Introduction

The V541 Cygni system (BD + 30° 3704; V = +10.35; B – V = 0.35) is a detached eclipsing binary consisting of a pair of B9.5V stars with an eccentric orbit ($a = 42.826\, R_S$, $e = 0.479$), orbital inclination close to 2/π (i = 89°.88), orbital period of P = 15.34 days, masses $m_1 = m_2 = 2.24\, M_S$, radius $R_1 = 1.88\, R_S$ and $R_2 = 1.79\, R_S$ for primary and secondary star, respectively (Lacy 1998).

It was discovered by Kulikowski (1948) and the first photoelectric light curve of V541 Cyg has been obtained by Khaliullin (1985) who also realized that this binary could be an important test-case for general relativity theory (GRT) because the apsidal motion rate expected from GRT is significantly larger than the classical (Newtonian) apsidal motion arising from the tidal and rotational distortions of the component stars. It is worthwhile to recall that Khaliullin (1985) evaluated the apsidal motion rate from his own observations of times of minima and from times of minima obtained by reanalysis of the photographic observations of Karpowicz (1961). Thus, from the data available at that time, Khaliullin (1985) found good agreement between the observed apsidal motion rate of V541 Cyg of $\dot{\omega}_{\text{obs}} = (0.90 \pm 0.15)\,\text{deg/cy}$ and the theoretical combined general relativistic and classical apsidal motion of $\dot{\omega}_{\text{GR+CL}} = (0.97 \pm 9)\,\text{deg/cy}$.

However, some results reported by several researchers (Wolf 1995; Guinan, Maley & Marshall 1996; and Lacy 1998) which are based on more numerous accurate eclipse timings than were available to Khaliullin, show that the observed apsidal motion rate is significantly slower than initially estimated by Khaliullin (1985).

2. Problematic

When this rate is compared with the expected theoretical rate due to general relativistic and classical effects it is found that there is a discrepancy in that the observed rate is significantly slower than expected. Furthermore, this discrepancy means that V541 Cyg joins V1143 Cyg, V459 Ca and AS Cam in having an observed apsidal advance rate significantly less than that predicted from theory. Since the general relativistic rate is 5 times the classical rate in V541 Cyg, suspicion falls directly on the GRT an otherwise well confirmed theory observationally and experimentally. It seems that the fate of V541 Cyg is similar to that of DI Her which has resisted explanation for 30 years (Guinan & Maloney 1985; Guinan, Marshall & Maloney 1994) but finally its mystery has been clarified by Albrecht *et al*.; (2009). In this paper, our model is partly based on the results of Lacy (1998) who used the models of Hejlesen (1987), and Claret & Giménez (1992), and Claret & Giménez (1993); Eqs. [1-4], to estimate: the apsidal motion rate due to classical effects (tidal and rotational distortions) of $\dot{\omega}_{\rm CL} = (0.147 \pm 0.023)\,\text{deg/cy}$, and the general relativistic rate is $\dot{\omega}_{\rm GR} = (0.740 \pm 0.018)\,\text{deg/cy}$. So the total rate should be

$$\dot{\omega}_{\rm GR+CL} = (0.89 \pm 0.03)\,\text{deg/cy}. \tag{1}$$

The observed rate of

$$\dot{\omega}_{\rm obs} = (0.60 \pm 0.10)\,\text{deg/cy}, \tag{2}$$

is significantly slower than the theoretical prediction (1) in which the general relativistic term is clearly the dominant one.

3. Model

Our model is entirely based on the hypothesis of retrograde spin-orbit coupling that claims that: *the retrograde spin-orbit coupling of binary systems causes orbital plane precession in direction opposite to the relativistic apsidal motion when the spin angular momentum vector* **S** *is not aligned with the orbital angular momentum vector* **L**. In fact, the concept of spin-orbit coupling precession is not new idea since it is well-known as a geodetic precession (De Sitter 1916a, 1916b; Robertson 1938; Barker & O'Connell 1970; Damour & Ruffini 1974; Barker & O'Connell 1975), a direct consequence of Einstein's GRT and is exclusively investigated in compact stellar objects like, *e.g*., pulsars, neutron stars, and white dwarfs (Barker & O'Connell 1976; Damour & Deruelle 1985, 1986; Bailes 1988; Damour & Taylor 1992; Lai, Bildsten & Kapsi 1995; Stairs, Thorsett & Arzoumanian 2004; Kramer et al. 2006; Lorimer et al. 2006). For example, to study the geodetic precession of a given double pulsar (pulsar system consists of two pulsars orbiting the common center of mass) we can use the standard formula derived by Barker & O'Connell (1975):

$$\psi(\text{rad/s}) = \frac{3\pi G m_1 (q + \frac{1}{3}Q)}{ac^2(1-e^2)p}\ , \tag{3}$$

where $q = m_2/m_1$ and $Q = m_2/(m_1+m_2)$ are the masse ratios; m_1 and m_2 are the masses of pulsars; G is the gravitational constant; c is the light speed in vacuum; and a, e, p are the orbital elements: semi major axis, eccentricity and period (all given in SI units), respectively.

ψ is in fact the angular velocity of the spin vector $\mathbf{\Omega}$ that precesses around the orbital angular momentum $\mathbf{L}$ as long as $\mathbf{\Omega}$ is not parallel to $\mathbf{L}$, *i.e.*, the misalignment angle between $\mathbf{\Omega}$ and $\mathbf{L}$, is different from zero. Thus, quantitatively and qualitatively, the formula (3) describes us, only, the *prograde* precession of orbital plane due to the spin-orbit coupling but we cannot use it for the *retrograde* precession. Furthermore, the geodetic precession as a gravitational phenomenon is not systematically exploited *via* the ordinary (non-compact) eclipsing binary star systems such negligence or omission may be the causal source of the observed anomalous precession of V541 Cyg as we will see.

Now, we are arrived at our main goal, that is, the generalization of (3) to the retrograde precession of orbital plane of the ordinary eclipsing binary star systems. Therefore, to this end, we must transpose and generalize (3) *from* compact binary stellar objects *to* non-compact ones in which the prograde/retrograde precession, normally, occurs in one component of such a binary system. Hence, for the purpose of our model, the generalized expression for prograde/retrograde spin-orbit coupling precession rate of orbital plane may be simply derived from (3) by introducing the compactness function $A(\varepsilon)$ instead of 1/3 and the double-sign $\pm$ which means prograde and/or retrograde precession that characterized the binary system and after substitution, we get

$$\Psi(\text{rad/s}) = \pm\,\frac{3\pi G m_1\left(q + A(\varepsilon)Q\right)}{ac^2\left(1-e^2\right)p}\,, \tag{4}$$

and the compactness function is defined by

$$A(\varepsilon) = \exp(-k\varepsilon)\,, \tag{5}$$

where $k = 5.17$ is a dimensionless constant and $\varepsilon = GM/c^2R$ is the well-known compactness parameter. Noting that for the pulsar's standard physical parameter values, $A(\varepsilon)$ should reduce to 1/3 since in general $\varepsilon = 2.126340\times10^{-1}$. This modification is very necessary for our case since, here, we are exclusively dealt with the ordinary eclipsing binary star systems which are astrophysically different from stellar compact objects. Finally, by taking into account the prograde/retrograde spin-orbit coupling precession rate of orbital plane, ψ, and the combined general relativistic and classical rate of apsidal motion, $\omega_{\mathrm{GR+CL}}$, it follows that the *effective* theoretical rate should be

$$\dot{\omega}_{\mathrm{eff}} = \dot{\omega}_{\mathrm{GR+CL}} + \Psi(\text{rad/s})\,. \tag{6}$$

Consequently, in the framework of the present model, the expected theoretical apsidal motion rate of binary star system V541 Cyg must be recalculated, particularly, when Ψ represents a retrograde precession of orbital plane, that is

$$\Psi(\text{rad/s}) = -\,\frac{3\pi G m_1\left(q + A(\varepsilon)\,Q\right)}{a\,c^2\left(1-e^2\right)p}\,. \tag{7}$$

Here $A(\varepsilon) = 1$ since the compactness parameter is of the order $\varepsilon = 2.530340\times10^{-6}$ for primary and/or secondary star for the reason that V541 Cyg is an ordinary (non-compact) binary system. Thus, as theoretical evidence of our *hypothesis*, let us utilize the above formulae (6,7) to investigate the effective theoretical rate, $\dot{\omega}_{\text{eff}}$, of apsidal advance of V541 Cyg. With this aim, we have according to Lacy (1998) the orbital and physical elements of V541 Cyg which are already mentioned in the introduction; and the following physical constant values: the Sun's radius and mass $R_S = 695508$ km ; $M_S = 1.9891 \times 10^{30}$ kg ; gravitational constant

$G = 6.67384 \times 10^{-11}\ \text{m}^3\,\text{kg}^{-1}\,\text{s}^{-2}$ and light speed in vacuum $c = 299792458\ \text{m}\,\text{s}^{-1}$. With the knowledge of physical dimensions of Ψ, which is an angular velocity, and after converting the value of orbital period, P, in seconds and replacing all the physical quantities and constants with their numerical values into the formula (7), we get

$$\begin{aligned}\Psi &= -1.554384 \times 10^{-12}\ \text{rad/s} \\ &= -2.810509 \times 10^{-1}\ \text{deg/cy}\end{aligned}, \tag{8}$$

By substituting (1) and (8) into the formula (6), we find the value of the expected effective theoretical rate

$$\dot{\omega}_{\text{eff}} = 0.608950\ \ \text{deg/cy}. \tag{9}$$

This is in a good agreement with the observed value (2), namely, $\omega_{\text{eff}} = 0.60$ deg/cy . Also this result shows us the significance of the contribution of retrograde spin-orbit coupling precession to the observed apsidal motion of V541 Cyg since in terms of percentage we have $|\ \Psi\ | / \omega_{\text{obs}} = 46.84$ % .

However, the solution to the discrepancy in the observed apsidal motion rate of V541 Cyg raises the questions of how the stars' spin and orbital angular momenta became so misaligned. It seems unlikely that the two stars are formed in such a state, although it is not quietly clear at what *phase* in their relatively short lifetime ≈ 250 Myr (Lacy 1998) the misalignment between **S** and **L** occurred?

4. Conclusion

In this paper, we have established one model based on the hypothesis of the retrograde spin-orbit coupling, which stipulates that: the retrograde spin-orbit coupling of binary systems causes orbital plane precession in direction opposite to the relativistic apsidal motion when the spin angular momentum vector **S** is not aligned with the orbital angular momentum vector **L** , and by applying this model to binary system V541 Cyg, we have resolved the discrepancy between the observed apsidal motion rate of V541 Cyg and the expected theoretical rate caused by the general relativistic and classical (Newtonian) effects.

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