On the Orbital Period Change in the Recurrent Nova U Scorpii

Rebecca G. Martin¹, Mario Livio¹ and Bradley E. Schaefer²

ABSTRACT

The orbital period of the recurrent nova U Sco has been observed to decrease during the 1999 outburst. In an outburst mass is ejected from the surface of the white dwarf. The separation of the binary system widens and the orbital period increases. We find that magnetic braking between outbursts, mass transfer to the companion, and frictional angular momentum losses during outbursts are all too small to account for this unexpected change. We find, however, that if the secondary has a sufficiently strong magnetic field, \( B \approx 8 \times 10^3 \) G, then the ejected material can couple to it and corotate with the system. The ejected material gains angular momentum while the binary system loses it and the period decreases. If such a strong magnetic field is indeed present, then we predict that a period decrease should be observed also during the current 2010 outburst. If, however, the presence of such a field can be ruled out observationally, then the cause for the period decrease (if confirmed) remains unknown.

Subject headings: stars: binaries - stars: magnetic - stars: novae - stars individual (U Scorpii)

1. Introduction

Recurrent novae are cataclysmic variables with outbursts at intervals of \( 10 - 80 \) yr (Warner 1995; Webbink et al. 1987). They are binary systems in which mass is transferred from a main-sequence star or a red giant to a white dwarf by Roche-lobe overflow. The critical amount of mass that can be accreted on to the surface of a white dwarf prior to an outburst is a strongly decreasing function of the white dwarf mass (Truran & Livio 1986). At this mass limit, the temperature and density at the base of the accreted layer are high enough for hydrogen to ignite. The temperature then rises rapidly in a thermonuclear runaway (Starrfield, Sparks & Shaviv 1988) and the pressure becomes high enough, so that aided by radioactive decays, most of the accreted material is ejected. To account for the short timescale between the outbursts, the white dwarf in a recurrent nova system must have a mass close to the Chandrasekhar limit (e.g. Kato & Hachisu 1988, 1989).

During an outburst a finite amount of material is expelled on a short timescale of a few months. Because of the mass loss from the system, the binary separation widens and so the

¹Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
²Physics and Astronomy, Louisiana State University, Baton Rouge, LA, 70803
orbital period increases. Angular momentum is continually lost from the system between outbursts, mainly because of gravitational radiation for the closest systems and magnetic braking for the wider systems. These mechanisms both cause the period to decrease on a very long timescale. During the outburst itself the period can decrease, in systems with orbital periods shorter than about 8 hours, because a small amount of mass can be transferred to the companion (Shara et al. 1986) and also because of frictional angular momentum losses as the binary moves through the ejected material (Livio, Govarie & Ritter 1991).

There are now ten recurrent novae known in our galaxy (the tenth one was discovered last year; Pagnotta et al. 2009) and one system in the LMC. In this group, U Sco has the fastest decline rate of the light curve in past outbursts, and the shortest recurrence period (11 yr since the last outburst, Schaefer 2001). It has outbursts recorded in 1863, 1906, 1917, 1936, 1945, 1969, 1979, 1987, 1999 (Schaefer 2010a) and 2010 (Schaefer 2010b) and other have likely been missed because of its proximity to the Sun (Schaefer 2004). The companion to the white dwarf in the system is a subgiant (Schaefer 1990).

The 1999 outburst was detected by Schmeer (1999). In this outburst, the orbital period of U Sco has been observed to decrease (Schaefer, unpublished). Since the orbital period of U Sco is about 30 hours, it was expected to increase during an outburst (Livio, Govarie & Ritter 1991) and so in this paper we investigate how a period decrease could occur.

2. Outburst Model

We first consider a simple model of the outburst where the ejected material carries away the specific angular momentum of the white dwarf. We assume that all the material that has been accreted since the last outburst is ejected in the outburst and we consider the change to the orbital period when the mass is ejected.

The non-degenerate mass accumulated on to the surface of the white dwarf is very thin and so the pressure at the base of the layer is given approximately by

$$P = \frac{GM_1 \Delta m}{R_1^2} \frac{1}{4\pi R_1^2}$$

where $\Delta m$ is the accumulated mass and the white dwarf has mass $M_1$ and radius $R_1$. The envelope is ejected when the pressure at the surface of the white dwarf reaches a critical value of the order of $P_{\text{crit}} = 10^{20} \text{ dyn cm}^{-2}$ (e.g. Fujimoto 1982, MacDonald 1983). We find that the amount of mass that accumulates before a nova outburst is of order

$$\Delta m = 4\pi R_1^2 \frac{P_{\text{crit}}}{GM_1}$$

The angular momentum of the binary star system is given by

$$J = \frac{M_2 M_1}{M} a^2 \Omega$$

where $a$ is the separation of the two stars and the angular velocity, $\Omega$, is given by Kepler’s law

$$\Omega^2 = \frac{GM}{a^3}. \quad (4)$$

Here the mass of the companion star is $M_2$ and the total mass of the system is $M = M_1 + M_2$. Then we can express the angular momentum of the binary system as

$$J = \frac{M_2 M_1}{M^\frac{7}{2}} G^\frac{3}{2} \left(\frac{P}{2\pi}\right)^\frac{1}{2} = \frac{M_2 M_1}{M^\frac{5}{2}} G^\frac{1}{2} a^\frac{1}{2}. \quad (5)$$

With this we can find the change in the angular momentum of the system for a given period and a given change in the mass.

If the mass carries away its specific angular momentum then the angular momentum loss from the system is

$$\Delta J = -\Delta m a_1^2 \Omega \quad (6)$$

where $a_1$ is the distance of $M_1$ to the center of mass of the binary

$$a_1 = \frac{M_2}{M} a \quad (7)$$

so that with equations (3) and (6) we find

$$\frac{\Delta J}{J} = -\frac{\Delta m}{M} \frac{M_2}{M_1}. \quad (8)$$

By differentiating equation (5) we also have

$$\frac{\Delta J}{J} = \frac{\Delta M_1}{M_1} - \frac{1}{2} \frac{\Delta M}{M} + \frac{1}{2} \frac{\Delta a}{a} \quad (9)$$

where $\Delta M_1 = \Delta M = -\Delta m$ and $\Delta a$ is the corresponding change in the separation of the system (due to mass lost) during the outburst. Equating (8) and (9) we find

$$\frac{\Delta a}{a} = \frac{\Delta m}{M}. \quad (10)$$

As mass is lost from the system in the outburst the separation increases.

By differentiating equation (4) we find the period change during the outburst to be

$$\frac{\Delta P}{P} = -\frac{\Delta \Omega}{\Omega} = -\frac{1}{2} \frac{\Delta M}{M} + \frac{3}{2} \frac{\Delta a}{a} \quad (11)$$

and with equation (10) we find

$$\frac{\Delta P}{P} = 2 \frac{\Delta m}{M}. \quad (12)$$

Since $\Delta m > 0$ we see that the period of the system should increase during the outburst if the material carries away its specific angular momentum.
3. The Observed Period Change in U Sco

U Sco has a white dwarf with a mass \( M_1 = 1.55 \pm 0.24 M_\odot \) (Thoroughgood et al. 2001). The radius of a non-rotating white dwarf is given approximately by

\[
R_1 = 7.99 \times 10^8 \left[ \left( \frac{M_1}{M_{\text{ch}}} \right)^{-\frac{2}{3}} - \left( \frac{M_1}{M_{\text{ch}}} \right)^{\frac{2}{3}} \right]^{\frac{1}{2}} \text{ cm} \tag{13}
\]

where \( M_{\text{ch}} = 1.44 M_\odot \) is the Chandrasekhar mass (Nauenberg 1972), so the radius of the white dwarf in U Sco is \( R_1 = 0.003 R_\odot \). We take the mass to be close to the upper limit for that of a white dwarf that is accreting matter before a supernova occurs, so \( M_1 = 1.37 M_\odot \) (Hachisu et al. 2000a). This mass is consistent with the fact that U Sco has such frequent outbursts. With equation (2) we find the mass accumulated before the outburst to be \( \Delta m = 2.36 \times 10^{-6} M_\odot \), consistent with estimates by Hachisu et al. (2000b) and we assume that all of this mass is ejected in the outburst. The evolved companion star has a mass of \( M_2 = 0.88 M_\odot \) and a radius of \( R_2 = 2.1 R_\odot \) (Thoroughgood et al. 2001).

The orbital period of the binary before the 1999 outburst was measured to be \( P_1 = 1.2305521 \text{ d} \) (Schaefer 1990; Schaefer & Ringwald 1995). After the 1999 outburst the period was measured again and was observed to be \( P_f = 1.2305470 \text{ d} \) (Schaefer, unpublished). The relative change is therefore

\[
\frac{\Delta P}{P} = \frac{P_f - P_i}{P_i} = -4.1 \pm 0.8 \times 10^{-6}. \tag{14}
\]

As we showed in the previous section, if the ejected mass carries away its specific angular momentum then the period of the system should increase in the outburst. We now consider mechanisms that can decrease the orbital period, both during the outburst and between outbursts.

3.1. Magnetic Braking

Between outbursts, for the systems with relatively long orbital periods, like U Sco, magnetic braking provides the largest continual loss of angular momentum from the system. The rate of loss of angular momentum is given roughly by

\[
\dot{J}_{\text{MB}} = -5.83 \times 10^{-16} \left( \frac{R_1}{R_\odot} \right)^3 (\Omega \text{ yr})^3 M_\odot R_\odot^2 \text{ yr}^{-2} \tag{15}
\]

(Rappaport, Verbunt & Joss 1983). The timescale on which magnetic braking operates is

\[
\tau_{\text{MB}} = \frac{J}{\dot{J}_{\text{MB}}}, \tag{16}
\]

which gives for U Sco a timescale of about \( 2.4 \times 10^9 \text{ yr} \). The time between outbursts in U Sco may be as short as 7.9 yr while the inter-eruption times for the known adjacent eruptions are 10.8, 8.9, 10.4,
7.9, 11.8 and now 10.8 yr with an overall average of 10.3 yr (Schaefer 2005, 2010b). Because the magnetic braking timescale is much longer, it is expected to have very little effect on the observed orbital period. The magnetic braking rate may about an order of magnitude lower than the rate given here (Martin & Tout 2005), however, this would make its timescale even longer. Magnetic braking is more important for classical novae which have eruptions every ten thousand years or so.

3.2. Mass Accretion on to the Companion

Shara et al. (1986) took into account the fraction of the ejected mass $\beta$ that may be captured by the companion in the outburst and found the separation change to be

$$\frac{\Delta a}{a} = \frac{\Delta m}{M_1} \left( \frac{1 + 2\beta q - \beta}{1 + q} - \frac{2\beta}{q(q+1)} \right),$$

(compare to equation 10 where $\beta = 0$) where $q = M_2/M_1$. In the absence of strong magnetic effects the maximum value of $\beta$ is the fractional area of the companion’s accretion radius. In order for the separation to decrease during the outburst by mass accretion on to the companion we need

$$\beta < \frac{q}{2 + q - 2q^2}. \quad (18)$$

For U Sco with $q = 0.64$ this requires $\beta > 0.35$ which is highly unlikely in such a wide system.

3.3. Frictional Angular Momentum Losses

Livio, Govarie & Ritter (1991) further considered changes to the system because of frictional angular momentum losses as the binary moves through the common envelope created by the ejected material. This causes the separation of the system to decrease and so the period decreases too. However, they found that frictional angular momentum losses are high enough to actually cause a decrease in the separation only in the systems with the shortest periods of around a few hours. Since U Sco has a long orbital period of 30 hr, it is unlikely that this mechanism could cause the observed decrease in the orbital period.

3.4. A Potential Alternative Explanation

We cannot explain the observed period decrease with the usual mechanisms for angular momentum loss either between the outbursts (by magnetic braking) or during the outbursts (by mass accretion on to the companion or frictional angular momentum losses). In this section we consider whether the magnetic field of the secondary star, that is rotating synchronously with the orbit, could provide the required angular momentum loss during the outburst.
Suppose that the ejected mass takes away more angular momentum than its specific angular momentum. If the ejected mass is forced to corrotate with the binary orbit by coupling to the secondary star’s magnetic field, it would take angular momentum directly from the orbit as it is spun up. The angular momentum of the system before the outburst, $J_i$, and after the outburst, $J_f$, are found with equation (5) and the two observed periods. Then the observed change in the angular momentum of the system is

$$\Delta J_{\text{obs}} = J_f - J_i.$$ \hfill (19)

For U Sco we find that this angular momentum change is nearly four times larger than the specific angular momentum of the ejected mass.

The angular momentum of ejected material that corrotates with the binary up to a radial distance $R_c$ is given by

$$\Delta J = \Delta m R_c^2 \Omega_f.$$ \hfill (20)

Therefore, to account for the observed change in the system’s angular momentum, corrotation needs to be enforced up to

$$R_c = \sqrt{\frac{(-\Delta J_{\text{obs}})}{\Delta m} \frac{1}{\Omega_f}}.$$ \hfill (21)

For U Sco the corrotation radius is at $R_c = 5.5 R_\odot = 0.76 a$. Magnetic pressure and and ram pressure of the ejected material balance at the Alfvén radius given by

$$R_A = \left(\frac{\mu^2 M^2 G M_2}{\dot{M}^2}\right)^{\frac{1}{4}}.$$ \hfill (22)

where $\mu$ is the dipole moment of the secondary magnetic star with mass $M_2$ and $\dot{M}$ is the mass ejection rate. The material corrotates up to this radius and so we set $R_c = R_A$ and find the required dipole moment

$$\mu = \left(R_c^2 \dot{M}^2 G M_2\right)^{\frac{1}{4}}.$$ \hfill (23)

The average mass-loss rate is

$$\dot{M} = \frac{\Delta m}{\tau}$$ \hfill (24)

where $\tau$ is the timescale over which the mass is lost. We can take $\tau \approx 3$ months (the timescale on which the optical light curve drops back to quiescence, Matsumoto et al. 2003). The magnetic field strength at the stellar surface is given by

$$B = \frac{\mu}{R_2^3}.$$ \hfill (25)

From equations (22) to (24) we find that the secondary star would need to have a surface field strength of $B = 8.0 \times 10^3$ G in order to account for the observed period change in U Sco.
4. Discussion and Conclusions

The decrease in the orbital period of U Sco during the 1999 outburst, if confirmed, cannot be explained by evolutionary magnetic braking between outbursts, accretion of mass on to the companion or by frictional angular momentum losses. However, if there is a sufficiently strong magnetic field on the companion, then it is possible that the ejected material may be forced to couple with the binary orbit, thus removing angular momentum from it and decreasing the period of the binary.

Magnetic fields of the order of a few kilogauss on the secondary star have been suggested previously (e.g. Meyer-Hofmeister, Vogt & Meyer 1996; Warner 1996). While such strong fields are typical of magnetic Ap stars, they may be less common in the secondaries of cataclysmic variables. However, high magnetic fields have been discussed for cataclysmic variables of shorter periods by Meintjes & Jurua (2006). The subgiant companion in U Sco is expected to be synchronously rotating with the orbit, with a period of 30 hr, which is very fast for a subgiant. Studies of late-type stars show that high fields can be expected for fast rotators (e.g. Noyes, Weiss & Vaughan 1984). If the strong magnetic field of the companion is present, the period decrease should again occur in the 2010 outburst. Measurements of the orbital period after the 2010 outburst are therefore strongly encouraged.

We should also note that orbital period changes have been observed in binary systems not involving nova outbursts (e.g. V471 Tau, Skillman & Patterson 1987). In V471 Tau in particular, a decrease in the orbital period of the same order of magnitude as that in U Sco has been observed. Several authors have proposed that the decrease was caused by a change in the internal structure of the star that changes the non-negligible quadrupole moment (e.g. Warner 1988; Applegate & Patterson 1987). However, as it has been shown by Marsh & Pringle (1990), the proposed mechanisms could only work on timescales that are longer than the observed one (about 4 years) by more than an order of magnitude.

Applegate (1992) also proposed a mechanism for orbital period modulation in close, non-nova, binaries. His model relies on the gravitational coupling of the orbit to variations in the shape of a magnetically active star. For this model to work, however, mean subsurface fields of several kilogauss are required. If such fields are indeed present, then, as we have shown, the observed period change in U Sco (which does undergo nova outbursts) can be plausibly explained by coupling of the ejecta to the object. Limits on the parabolic term in the O-C diagram during quiescence also seem to indicate that Applegate’s mechanism does not operate in U Sco.

We thank Jim Pringle for helpful discussions.
REFERENCES

Applegate J. H., Patterson J., 1987, ApJ, 322, L99
Applegate J. H., 1992, ApJ, 385, 621
Fujimoto M., 1982a, ApJ, 257, 752
Fujimoto M., 1982b, ApJ, 257, 767
Hachisu I., Kato M., Kato T., Matsumoto M., Nomoto K., 2000a, ApJ, 534, L189
Hachisu I., Kato M., Kato T., Matsumoto K., 2000b, ApJ, 528, L97
Kato M., Hachisu I., 1988, ApJ, 329, 808
Kato M., Hachisu I., 1989, ApJ, 346, 424
Livio M., Govarie A., Ritter H., 1991, A&A, 246, 84
MacDonald J., 1983, ApJ, 267, 732
Marsh T. R., Pringle J. E., 1990, 365, 677
Martin R. G., Tout C. A., 2005, MNRAS, 358, 1036
Matsumoto K., Kato T., Hachisu I., 2003, PASJ, 55, 297
Meintjes P. J., Jurua E., 2006, MNRAS, 372, 1279
Meyer-Hofmeister E., Vogt N., Meyer F., 1996, A&A, 310, 519
Nauenberg M., 1972, ApJ, 175, 417
Noyes R. W., Weiss N. O., Vaughan A. H., 1984, ApJ, 287, 769
Pagnotta A., Schaefer B. E., Xiao L., Collazzi A. C., Kroll P., 2009, AJ, 138, 1230
Rappaport S., Verbunt F., Joss P. C., 1983, ApJ, 275, 713
Schaefer B. E., 1990, ApJ, 355, L39
Schaefer B. E., Ringwald F. A., 1995, ApJ, 447, L45
Schaefer B. E., 2001, IAUC, 7749
Schaefer B. E., 2004, IAUC, 8278
Schaefer B. E., 2005, ApJ, 621, L53
Schaefer B. E., 2010a, ApJS, 187, 275
Schaefer B. E., Harris B. G., Dvorak S., Templeton M., Linnolt M., 2010b, IAUC, 9111
Schmeer P., 1999, VSNET, vsnet-alert, 2688
Skillman D. R., Patterson J., 1988, AJ, 96, 976
Shara M. M., Livio M., Moffat A. F. J., Orio M., 1986, ApJ, 311, 163
Starrfield S., Sparks W. M., Shaviv G., 1988, ApJ, 325, L35
Thoroughgood T. D., Dhillon V. S., Littlefair S. P., Marsh T. R., Smith D. A., 2001, MNRAS, 327, 1323
Truran J. W., Livio M., 1986, ApJ, 308, 721
Warner B., 1988, Nat, 336, 129
Warner B., 1995, Cataclysmic Variable Stars, Cambridge, Cambridge University Press
Warner B., 1996, Ap&SS, 241, 263
Webbink R. F., Livio M., Truran J. W., Orio M., 1987, ApJ, 314, 653

This preprint was prepared with the AAS LaTeX macros v5.2.