The Light and Period Variations of the Eclipsing Binary BX Draconis

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Abstract

New CCD photometric observations of BX Dra were carried out on 26 nights during the period from 2009 April to 2010 June. The long-term photometric behaviors of the system are obtained from detailed studies of the period and light variations, based on historical data and our new observations. All available light curves display total eclipses at secondary minima and inverse O’Connell effects with Max I fainter than Max II, which were satisfactorily modeled by adding a slightly time-varying hot spot on the primary star. A total of 87 times of minimum lights spanning over ~ 74 yr, including our 22 timing measurements, were used for ephemeris computations. A detailed analysis of the O − C diagram disclosed that the orbital period shows an upward parabola in combination with a sinusoidal variation. The continuous increase of period at a rate of +5.65 × 10^{-7} d yr^{-1} is consistent with that calculated from the Wilson–Devinney synthesis code. It can be interpreted as a mass transfer from the secondary star to the primary at a rate of 2.74 × 10^{-7} M_{\odot} yr^{-1}, which is one of the largest rates between components of the contact system. The most likely explanation of the sinusoidal variation having a period of 30.2 yr and a semiamplitude of 0.0062 d is a light-travel-time effect due to the existence of a circumbinary object. We suggest that BX Dra is probably a triple system, consisting of a primary star with a spectral type of F0, its secondary component of spectral type F1–2, and an unseen circumbinary object with a minimum mass of M_{3} = 0.23 M_{\odot}.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual (BX Draconis) — stars: spots — techniques: photometric

1. Introduction

BX Dra (GSS 4192-0448, 2MASS J16061736+6245460, HIP 78891) was discovered to be a short-period variable by Strohmeier (1959), and classified as an RR Lyr-type star with a period of 0.561192 d by Strohmeier, Knigge, and Ott (1965). Some doubt as to this classification and hints about a binary system together with the first detailed analysis of the light source or a spot.

Although eclipsing minimum epochs have been reported assiduously by numerous workers, the period variation of BX Dra has not yet been studied in detail. In this article, we present and discuss long-term photometric behaviors of the binary system together with the first detailed analysis of the O − C diagram, based on our new CCD observations as well as historical data.

2. CCD Photometric Observations

New CCD photometric observations of BX Dra were carried out during two observing seasons in 2009 April and in 2010 April, May, and June, using BVR filters attached to the 61 cm reflector at Sobaeaksan Optical Astronomy Observatory (SOAO) in Korea. The observations of the 2009 season (SOAO09) were made on eight nights using a SITE 2K CCD camera, which has 2048 × 2048 pixels and an image field-of-view (FOV) of ~20.5 × 20.5 at the F/13.5 Cassegrain focus of the telescope. The observations of the 2010 season (SOAO10) were made on 18 nights using an FLI IMG4301E 2K CCD camera. The new CCD chip has 2084 × 2084 pixels and an FOV of ~20.9 × 20.9. The instruments and reduction methods were the same as those described by Lee, Kim, and Koch (2007) and Lee et al. (2011). GSC 4192-0521 (V = 11.0) and GSC 4192-0617 (V = 11.3) that are in the same observing
ephemeris for our hot-spot model described in section 3. The magnitudes and orbital phases, which were computed using the plotted in figure 2 to show the relation between differential a sample is listed in table 1. The light curves of BX Dra are marked by C and K, respectively. The 1/ESC shown in figure 1, in which the comparison and check stars during our observing runs. An observed image in SOAO09 is shown in figure 1, in which the comparison and check stars, respectively. We detected no variation of the difference in brightness between these two stars during our observing runs. An observed image in SOAO09 is shown in figure 1, in which the comparison and check stars are marked by C and K, respectively. The 1σ values of the dispersion of the (K−C) differences are \( \sim \pm 0.009\) mag in all bandpasses.

From the SOAO observations, we obtained 1620 individual points in the B bandpass, 1622 in V, and 1617 in R, and a sample is listed in table 1. The light curves of BX Dra are plotted in figure 2 to show the relation between differential magnitudes and orbital phases, which were computed using the ephemeris for our hot-spot model described in section 3. The open circles and plus symbols are the measures of the 2009 and 2010 seasons, respectively.

### Table 1. CCD photometric observations of BX Dra in 2009 and 2010.

| HJD       | \( \Delta B \) | HJD       | \( \Delta V \) | HJD       | \( \Delta R \) |
|-----------|-----------------|-----------|----------------|-----------|----------------|
| 2009      | 2454927.16950   | −1.102    | 2454927.16762  | −0.773    | 2454927.16621  | −0.571 |
| 2454927.17432 | −1.108        | 2454927.17257 | −0.758    | 2454927.17122 | −0.558 |
| 2454927.17906 | −1.109        | 2454927.17731 | −0.765    | 2454927.17597 | −0.565 |
| 2454927.18381 | −1.102        | 2454927.18206 | −0.759    | 2454927.18071 | −0.572 |
| 2454927.18856 | −1.110        | 2454927.18680 | −0.764    | 2454927.18545 | −0.573 |
| 2010      | 2455303.26231  | −1.065    | 2455303.26331  | −0.724    | 2455303.26406  | −0.521 |
| 2455303.26501 | −1.077        | 2455303.26602 | −0.742    | 2455303.26677 | −0.529 |
| 2455303.26770 | −1.084        | 2455303.26872 | −0.749    | 2455303.26946 | −0.547 |
| 2455303.27049 | −1.105        | 2455303.27163 | −0.774    | 2455303.27245 | −0.558 |
| 2455303.27351 | −1.125        | 2455303.27465 | −0.792    | 2455303.27548 | −0.588 |

* A sample is shown here; the full version is available in its entirety in a machine-readable form in the PASJ online edition (http://pasj.asj.or.jp/v65/n1/650001/).

3. Light-Curve Analysis and Spot Model

Our light curves of BX Dra show a flat bottom at the secondary minimum the same as historical ones, which means that this system belongs to the A-subtype of W UMa-type stars. In addition, the new data show the inverse O'Connell effect with Max I (at phase 0.25) fainter than Max II (at phase 0.75) by \( \sim 0.014 \) mag for the B band and 0.008 mag for V, while the light levels in R equal at the quadratures. These features usually indicate wavelength-dependent spot activity on the component stars. In order to obtain a unique set of photometric solutions, we analyzed all available light curves (SGG, ZOLA, KIM, and SOAO) using contact mode 3 of the 2003 version of the Wilson–Devinney synthesis code (Wilson & Devinney 1971, hereafter W–D). For this purpose, we normalized the level at phase 0.75 and used a weighting scheme identical with that for the eclipsing binary GW Gem (Lee et al. 2009a). Table 2 lists the light-curve sets for BX Dra analyzed in this article and the standard deviations (\( \sigma \)) of a single observation.

The binary parameters of BX Dra were initialized in a manner similar to that for the contact systems, BX Peg (Lee et al. 2004) and AA UMa (Lee et al. 2011). The effective temperature of the more massive primary star was fixed at \( T_1 = 6980 \) K, according to the spectral type F0 classified by Pych et al. (2004). Linear bolometric \((X, Y)\) and monochromatic \((x, y)\) limb-darkening coefficients were interpolated from the values of Van Hamme (1993) in concert with the model atmosphere option. The initial value of the mass ratio \((q = m_2/m_1)\) was taken from Pych et al. (2004). Throughout analyses, synchronous rotation was assumed, and a third light source \((\ell_3)\) was considered. In addition, since the atmosphere of both components should lie close to the boundary between the radiative and convective envelopes, the gravity-darkening exponents \((q)\) and the bolometric albedos \((A)\) were investigated at standard values of \((A, q) = (1.0, 1.0)\) for the former and \((0.5, 0.32)\) for the latter. Because the convective model gives a better fit than the radiative model, the common envelope was treated as a convective atmosphere in all subsequent syntheses.
Fig. 2. $BVR$ light curves of BX Dra observed in 2009 and 2010. Because of the high density of points, many of the 2009 measures cannot be seen individually.

Table 2. Light-curve sets for BX Dra.

| Reference | Season | Data type | $\sigma^*$  |
|-----------|--------|-----------|-------------|
| SGG       | 2006   | $B$       | 0.0078      |
|           |        | $V$       | 0.0062      |
|           |        | $I$       | 0.0058      |
| ZOLA      | 2006   | $B$       | 0.0115      |
|           |        | $V$       | 0.0121      |
|           |        | $R$       | 0.0120      |
|           |        | $I$       | 0.0113      |
| KIM       | 2008   | $B$       | 0.0209      |
|           |        | $V$       | 0.0119      |
| SOAO      | 2009   | $B$       | 0.0074      |
|           |        | $V$       | 0.0087      |
|           |        | $R$       | 0.0093      |
| 2010      | $B$    | 0.0098    |
|           | $V$    | 0.0070    |
|           | $R$    | 0.0062    |

* In units of total light at phase 0.75.

In tables 3 and 4, parentheses represent adjusted parameters and subscripts 1 and 2 refer to the primary and secondary stars which are eclipsed at Min I and Min II, respectively.

First of all, we analyzed simultaneously all of the light curves of BX Dra, permitting no spots. The unspotted solution is listed in the second column of table 3 and the $V$ residuals from the analysis are plotted in the left panels of figure 3. Similar patterns exist in the other bandpasses. As shown in these panels, the model light curves do not well fit with the observed ones at all. In contact binaries, the discrepancies may be caused by local photospheric inhomogeneities, such as a cool spot on a magnetically active component and/or a hot spot due to an impact of a mass transfer between the components (see, e.g., Lee et al. 2009b, 2010). Thus, spot models were added to fit the light variation. Because the seasonal variations of the light residuals are not large, we reanalyzed the data sets while considering either a hot spot or a cool one on individual components. The results are given in columns (3)–(6) of table 3 together with the spot parameters. The residuals from the hot-spot model (Hot 1) on the primary component are plotted in the right panels of figure 3. Based on these results, we can see that the Hot 1 model gives slightly smaller values for the sum of the squared residuals $[\sum W(O - C)^2]$ than the other models, and that a large hot spot on the primary star has been sufficient for the light-curve representations of BX Dra. Nonetheless, it is difficult to distinguish between the spot models through only the light-curve analysis, because the differences among them are small.

Finally, to understand long-term spot behaviors in detail, we solved five historical data sets separately using the hot-spot
model on the primary star. In this procedure, we adjusted only the orbital ephemeris, spot, and luminosity parameters among the Hot 1 model parameters. The final results are given in table 4, and the normalized V observations with the model light curves are plotted in figure 4. The result of the spot modeling reveals that the light ratios have not changed, and the seasonal light curves were capable of being represented by a slightly variable hot spot. Because the colatitude and longitude of the spot have been almost constant with time, and the components of BX Dra should have shallow convective shells and at most weak magnetic activity, as surmised from their temperatures, it is possible to regard the main cause of the variability of the spot have been almost constant with time, and the intrinsic light variations of BX Dra could be caused by the simultaneous existence of a hot spot due to mass transfer and a magnetic spot on a component, but individual trials for the two spot configurations did not give a better fit than the single hot-spot model. In all procedures, we looked for a possible third light source (l3), suggested by SGG, but found that the parameter remains indistinguishable from zero within its error range.

In order to determine the physical properties of the binary system, we analyzed the radial-velocity curves of Pych et al. (2004) using our light-curve parameters of the Hot 1 model. From the photometric and spectroscopic results, the absolute dimensions of BX Dra were determined and listed in table 5, where the radius (R) is the mean-volume radius evaluated from the tabulations of Mochnacki (1984). The luminosity (L) and the bolometric magnitude (Mbol) were computed by adopting Teff = 5780 K and Mbol = 4.73 for solar values. To estimate the uncertainty in the luminosity, it was assumed that the temperature of each component has an error of 200 K in accordance with the unreliability in the spectral classification. For the absolute visual magnitude (MV), we used bolometric corrections (BCs) derived from the relation between log T and BC given by Torres (2010). The absolute parameters presented in this paper are consistent with those of SGG within the uncertainties.

Table 3. Binary parameters obtained by fitting all light curves simultaneously.

| Parameter                  | Without spot | Cool 1 | Cool 2 | Hot 1 | Hot 2 |
|----------------------------|--------------|--------|--------|-------|-------|
| T0 (HJD)$^1$               | 810.58987(12)| 810.59009(13)| 810.58995(13)| 810.58976(12)| 810.58970(12)|
| P (d)                      | 0.57902455(4)| 0.57902476(4)| 0.57902477(4)| 0.57902479(4)| 0.57902472(4)|
| dP/dt ($\times 10^{-9}$)   | 1.386(12)    | 1.303(11)    | 1.302(11)    | 1.288(11)    | 1.317(11)    |
| T1 (K)                     | 6980         | 6980         | 6980         | 6980         | 6980         |
| T2 (K)                     | 6979(2)      | 6707(2)      | 6995(2)      | 6758(4)      | 6805(3)      |
| i (°)                      | 80.63(6)     | 80.66(5)     | 82.42(8)     | 81.80(6)     | 82.18(8)     |
| q ($= m_2/m_1$)            | 0.2884(5)    | 0.2874(5)    | 0.2871(4)    | 0.2884(5)    | 0.2882(5)    |
| $\Omega_1 = \Omega_2$      | 2.3475(16)   | 2.3462(15)   | 2.3404(14)   | 2.3308(14)   | 2.3293(16)   |
| L1/(L1 + L2)$_B$           | 0.7432(5)    | 0.7828(6)    | 0.7407(4)    | 0.7729(4)    | 0.7660(5)    |
| L1/(L1 + L2)$_V$           | 0.7435(5)    | 0.7744(5)    | 0.7416(4)    | 0.7660(4)    | 0.7606(4)    |
| L1/(L1 + L2)$_R$           | 0.7437(4)    | 0.7685(5)    | 0.7421(4)    | 0.7612(4)    | 0.7568(4)    |
| L1/(L1 + L2)$_I$           | 0.7437(4)    | 0.7639(4)    | 0.7424(4)    | 0.7575(3)    | 0.7539(4)    |
| r1 (pole)                  | 0.4791(4)    | 0.4792(4)    | 0.4804(3)    | 0.4828(3)    | 0.4832(4)    |
| r1 (side)                  | 0.5218(5)    | 0.5219(5)    | 0.5237(5)    | 0.5272(5)    | 0.5277(5)    |
| r1 (back)                  | 0.5542(7)    | 0.5543(7)    | 0.5565(6)    | 0.5614(7)    | 0.5620(7)    |
| r2 (pole)                  | 0.2803(6)    | 0.2799(6)    | 0.2811(5)    | 0.2846(6)    | 0.2849(6)    |
| r2 (side)                  | 0.2953(8)    | 0.2949(7)    | 0.2964(7)    | 0.3007(8)    | 0.3010(8)    |
| r2 (back)                  | 0.3513(18)   | 0.3506(17)   | 0.3542(16)   | 0.3638(20)   | 0.3648(21)   |

| Spot parameters:            |              |        |        |       |       |
| Colatitude$_1$ (°)          | —             | 22.3   | —      | 8.5   | —     |
| Longitude$_1$ (°)           | —             | 188.8  | —      | 11.5  | —     |
| Radius$_1$ (°)              | —             | 35.7   | —      | 36.5  | —     |
| $T_{\text{spot1}}/T_{\text{local1}}$ | —         | 0.758  | —      | 1.361 | —     |
| Colatitude$_2$ (°)          | —             | —      | 24.1   | —     | 33.3  |
| Longitude$_2$ (°)           | —             | —      | 9.6    | —     | 186.0 |
| Radius$_2$ (°)              | —             | —      | 50.4   | —     | 33.2  |
| $T_{\text{spot2}}/T_{\text{local2}}$ | —         | —      | 0.723  | —     | 1.259 |

| $\Sigma W(O - C)^2$         | 0.0151        | 0.0129 | 0.0126 | 0.0121 | 0.0126 |

$^1$ Cool 1, a cool spot on the primary; Cool 2, a cool spot on the secondary; Hot 1, a hot spot on the primary; Hot 2, a hot spot on the secondary.
$^\dagger$ HJD 2449000 is suppressed.
Fig. 3. Left and right panels show the light residuals from the solutions without a spot and with a hot spot (Hot 1) listed in table 3, respectively. The data refer to the \( V \) bandpass.

Table 4. Year-to-year variations of the spot and luminosity parameters.

| Parameter                  | SGG        | ZOLA       | KIM        | SOAO09     | SOAO10     |
|----------------------------|------------|------------|------------|------------|------------|
| \( T_0 \) (HJD)*           | 3767.66365(7) | 3905.47131(5) | 4581.20182(19) | 4932.09274(8) | 5314.25365(7) |
| \( P \) (d)                | 0.5790304(16) | 0.5790455(73) | 0.5790273(20) | 0.5790446(45) | 0.5790425(13) |
| Colatitude\(_1\) (°)       | 8.5        | 8.5        | 8.8        | 8.5        | 8.3        |
| Longitude\(_1\) (°)        | 10.9       | 11.5       | 11.5       | 11.5       | 11.5       |
| Radius\(_1\) (°)           | 36.1       | 39.1       | 38.5       | 39.6       | 36.5       |
| \( T_{\text{spot1}}/T_{\text{local1}} \) | 1.365      | 1.369      | 1.386      | 1.340      | 1.370      |
| \( L_1/(L_1 + L_2)_R \)    | 0.7729(4)  | 0.7729(3)  | 0.7729(10) | 0.7729(4)  | 0.7729(2)  |
| \( L_1/(L_1 + L_2)_V \)    | 0.7660(3)  | 0.7660(3)  | 0.7660(5)  | 0.7660(3)  | 0.7660(2)  |
| \( L_1/(L_1 + L_2)_R \)    | —          | 0.7612(3)  | —          | 0.7612(3)  | 0.7612(2)  |
| \( L_1/(L_1 + L_2)_I \)    | 0.7575(2)  | 0.7575(3)  | —          | —          | —          |
| \( \Sigma W(O - C)^2 \)    | 0.0092     | 0.0119     | 0.0113     | 0.0121     | 0.0116     |

* HJD 2450000 is suppressed.
4. Orbital Period Study

From the SOAO observations, 12 weighted times of the minimum light and their errors were determined using the method of Kwee and van Woerden (1956). In addition to these, eight and two eclipse timings were newly determined from individual measurements of KIM and ZOLA, respectively. Including our measurements, a total of 87 timings (36 photographic, 9 photoelectric, and 42 CCD) have been collected from the database of Kreiner, Kim, and Nha (2001) and from more recent literature. All available photoelectric and CCD timings are listed in table 6. Because many timings of the system have been published without errors, the following standard deviations were assigned to timing residuals based on the observational method: ±0.0316 d for photographic plate, ±0.0019 d for photoelectric measurement, and ±0.0012 d for CCD. Relative weights for the period analysis of BX Dra were then derived from the inverse squares of these values.

### Table 5. Absolute parameters of BX Dra.

| Parameter | Primary | Secondary |
|-----------|---------|-----------|
| $a (R_\odot)$ | 4.058(87) |
| $V_0$ (km s$^{-1}$) | −25.6(2.2) |
| $M$ ($M_\odot$) | 2.08(10) | 0.60(4) |
| $R$ ($R_\odot$) | 2.13(5) | 1.28(3) |
| log $g$ (cgs) | 4.10(3) | 4.00(3) |
| $\rho$ (g cm$^{-3}$) | 0.30(2) | 0.41(4) |
| $T$ (K) | 6980(200) | 6758(200) |
| $L$ ($L_\odot$) | 9.66(1.18) | 3.05(38) |
| $M_{bol}$ (mag) | 2.27(13) | 3.52(14) |
| $BC$ (mag) | 0.03 | 0.02 |
| $M_V$ (mag) | 2.24(13) | 3.50(14) |

Fig. 4. Normalized $V$ observations with the fitted model light curves. The continuous curves represent the solutions obtained from the hot-spot model parameters listed in table 4.
### Table 6. Photoelectric and CCD timings of the minimum light for BX Dra.

| HJD (2400000+) | Error | Epoch | O–C_full | Min | Reference                  |
|----------------|-------|-------|----------|-----|----------------------------|
| 48528.63       | ±0.0003 | 582.0 | −0.0019  | I   | Agerer and Hübischer (1996)|
| 49810.5926     | ±0.0004 | 1272.5 | 0.0003   | II  | Agerer and Hübischer (1999)|
| 49811.4614     | ±0.0003 | 1889.0 | 0.0004   | I   | Agerer and Hübischer (1999)|
| 49812.3275     | ±0.0005 | 1960.0 | 0.0020   | I   | Agerer and Hübischer (1999)|
| 49840.4122     | ±0.0001 | 4407.0 | −0.0025  | I   | Diethelm (2002)            |
| 50147.5838     | ±0.0003 | 4727.0 | 0.0007   | II  | Agerer and Hübischer (2000)|
| 50547.4042     | ±0.0001 | 6818.5 | 0.0005   | II  | SGG                        |
| 50904.3743     | ±0.0003 | 6842.5 | −0.0002  | II  | SGG                        |
| 50945.4868     | ±0.0001 | 6846.0 | 0.0009   | I   | SGG                        |
| 51256.4227     | ±0.0001 | 6880.5 | −0.0001  | II  | SGG                        |
| 51270.6090     | ±0.0001 | 6891.0 | 0.0006   | I   | SGG                        |
| 51286.3600     | ±0.0003 | 6918.5 | 0.0002   | I   | SGG                        |
| 51294.5882     | ±0.0001 | 6941.5 | −0.0002  | II  | SGG                        |
| 51297.6127     | ±0.0003 | 7072.0 | −0.0006  | I   | ZOLA                       |
| 51362.3600     | ±0.0003 | 7075.5 | −0.0021  | II  | ZOLA                       |
| 51377.5815     | ±0.0001 | 8147.0 | −0.0001  | I   | Nelson (2009)              |
| 51457.1205     | ±0.0002 | 8228.5 | −0.0002  | II  | KIM                        |
| 51458.1202     | ±0.0003 | 8239.0 | 0.0021   | I   | KIM                        |
| 51458.4092     | ±0.0006 | 8244.0 | 0.0025   | I   | KIM                        |
| 51458.6132     | ±0.0007 | 8247.5 | 0.0009   | II  | KIM                        |
| 51458.8150     | ±0.0001 | 8251.0 | 0.0012   | I   | KIM                        |
| 51459.4133     | ±0.0001 | 8267.0 | −0.0001  | I   | Hübischer, Steinbach, and Walter (2009)|
| 51460.2050     | ±0.0006 | 8277.0 | 0.0013   | I   | KIM                        |
| 51468.5130     | ±0.0003 | 8418.5 | 0.0024   | II  | KIM                        |
| 51468.6007     | ±0.0005 | 8420.0 | 0.0018   | I   | KIM                        |
| 51493.1224     | ±0.0003 | 8843.5 | −0.0007  | II  | This paper (SOAO)          |
| 51493.2095     | ±0.0003 | 8845.0 | 0.0001   | I   | This paper (SOAO)          |
| 51494.1202     | ±0.0003 | 8848.5 | 0.0002   | II  | This paper (SOAO)          |
| 51494.3595     | ±0.0003 | 8861.0 | 0.0016   | I   | Brá et al. (2009)          |
| 51494.2017     | ±0.0002 | 8878.0 | 0.0003   | I   | This paper (SOAO)          |
| 51495.8323     | ±0.0012 | 8886.0 | −0.0014  | I   | Diethelm (2009)            |
| 51514.2540     | ±0.0004 | 9505.0 | −0.0005  | I   | This paper (SOAO)          |
| 51532.2826     | ±0.0002 | 9527.5 | −0.0000  | II  | This paper (SOAO)          |
| 51532.2046     | ±0.0001 | 9536.0 | 0.0001   | I   | This paper (SOAO)          |
| 51537.1261     | ±0.0002 | 9544.5 | −0.0002  | II  | This paper (SOAO)          |
| 51535.1545     | ±0.0002 | 9567.0 | 0.0000   | I   | This paper (SOAO)          |
| 51535.2189     | ±0.0002 | 9570.5 | −0.0002  | II  | This paper (SOAO)          |
| 51535.3048     | ±0.0002 | 9572.0 | −0.0012  | I   | This paper (SOAO)          |
| 51535.4074     | ±0.0003 | 9574.0 | −0.0002  | I   | This paper (SOAO)          |
As mentioned in section 1, SGG reported that the period change of BX Dra could be represented by a parabolic variation. After testing several other forms, including this possibility, we found that the eclipse timing displays a sinusoidal variation superposed on an upward parabola, rather than varying in a monotonic pattern. Using the PERIOD04 program (Lenz & Breger 2005), we expected to see if the residuals from the quadratic fit represent real and periodic variations. As shown in the small box of the top panel of figure 5, a frequency of $f = 0.0000636 \text{ cycle d}^{-1}$ was detected, corresponding to $\sim 25$ yr. The periodic variation suggests a light-travel time (LTT) effect driven by the existence of a third component orbiting the eclipsing binary. Thus, the following quadratic plus LTT ephemeris was fitted to the complete timing data:

$$C = T_0 + PE + AE^2 + \tau_3,$$

where $\tau_3$ is the LTT due to a circumbinary object in the system (Irwin 1952, 1959) and includes five parameters $(a_{12}\sin i_3, e, \omega, n, T)$. The Levenberg–Marquardt algorithm (Press et al. 1992) was applied to solve the eight parameters of the ephemeris; the results are summarized in table 7, together with related quantities. Our absolute dimensions given in table 5 have been used for these and subsequent calculations.

The $O-C$ residuals calculated from the linear terms in equation (1) are plotted in the top panel of figure 5, where the continuous curve represents the quadratic term of this ephemeris. The middle panel displays the LTT orbit, and the bottom panel shows the residuals from the complete ephemeris. These appear as $O-C_{\text{full}}$ in the fourth column of table 6. As displayed in the figure, the quadratic plus LTT ephemeris currently provides a good representation of all modern times of the minimum light. The LTT orbit has a period of $P_3 = 30.2$ yr, a semiamplitude of $K = 0.0062$ d, a projected orbital semi-major axis of $a_{12}\sin i_3 = 1.08$ AU, and an eccentricity of $e = 0.35$. The mass function of the circumbinary object becomes $f_3(M_3) = 0.00138 M_\odot$, and its minimum mass is $0.23 M_\odot$. Because only $\sim 62\%$ of the 30 yr period has been covered by the photometric and CCD data, future accurate timings are required to identify and understand the LTT effect.

As in the case of the contact binary AR Boo (Lee et al. 2009b) with a convective envelope, the quasi-sinusoidal period variation with small amplitudes may be produced by asymmetrical eclipse minima due to spot activity (Kalimeris et al. 2002) and/or the method of measuring the timings (Maceroni & van’t Veer 1994). The light-curve synthesis method gives more and better information with respect to the other methods, which do not consider spot activity and are based only on observations during minima (Lee et al. 2009b). Because five data sets of BX Dra were modeled for Hot 1 spot parameters, we calculated a minimum epoch for each eclipse in these data sets with the W–D code by means of adjusting only the ephemeris epoch ($T_0$). The results are listed in table 8 together with the previously tabulated timings for comparison, and are illustrated with the “X” symbol in figure 5. The differences between the published minima and those obtained by the synthesis model are significantly smaller than the observed amplitude (0.012 d) of the LTT variation. As shown in figure 5, the light-curve timings agree with our analysis of the $O-C$ diagram, and the periodic variation cannot result from the star-spot activity. Further, as shown in the fourth column of table 8, there are systematic runs of differences between them, which are negative for Min I and positive for Min II. These differences are caused by the hot spot on the primary star presented to the observer.

The quadratic term $(A)$ of equation (1) signifies a continuous period increase with a rate of $+ (5.65 \pm 0.07) \times 10^{-7} \text{ yr}^{-1}$, corresponding to a fractional period change of $+ (1.55 \pm 0.02) \times 10^{-9}$. This is very close to the value of $+1.29 \times 10^{-9}$ calculated from the W–D code, independently of the eclipse timings. The most common explanation of the period increase is a mass transfer from the less-massive secondary star to the primary component. Under the assumption of conservative mass transfer, the transfer rate was calculated to be $2.74 \times 10^{-7} M_\odot \text{ yr}^{-1}$. This value is larger than those recently derived for other overcontact systems [e.g., $2.0 \times 10^{-8}$ for BV Dra (Yang et al. 2009), $1.5 \times 10^{-7}$ for AR Boo (Lee et al. 2009b), $7.4 \times 10^{-8}$ for V1191 Cyg (Zhu et al. 2011), and $6.6 \times 10^{-8}$ for AA UMa (Lee et al. 2011), all in units of $M_\odot \text{ yr}^{-1}$).

### 5. Summary and Discussion

In this article, we have presented the long-term photometric behaviors of BX Dra from detailed analyses of the light curves and the $O-C$ diagram based on both historical and new observations. The results from these analyses can be summarized as follows:

1. Historical light curves of BX Dra, as well as our own, display total eclipses at secondary minima and inverse O’Connell effects with Max I fainter than Max II. The asymmetric light curves can satisfactorily be explained by the spot model. The slightly variable hot spot on the primary star permits good light-curve representations for the system.

2. The orbital period of BX Dra has varied through a combination of an upward parabola and a sinusoidal variation with a period of 30.2 yr and a semiamplitude

| Parameter | Value | Units |
|-----------|-------|-------|
| $T_0$ | 2449810.58844(36) | HJD |
| $P$ | 0.579024741(46) | d |
| $A$ | $4.476(56) \times 10^{-10}$ | d |
| $a_{12}\sin i_3$ | 1.08(13) | AU |
| $\omega$ | 61.8(3.8) | $^\circ$ |
| $e$ | 0.350(94) | |
| $n$ | 0.0326(13) | deg d$^{-1}$ |
| $T$ | 2450417(140) | HJD |
| $P_3$ | 30.2(1.2) | yr |
| $K$ | 0.00615(74) | d |
| $f(M_3)$ | 0.00138(17) | $M_\odot$ |
| $M_3\sin i_3$ | 0.23 | $M_\odot$ |
| $dP/dt$ | $5.647(70) \times 10^{-7}$ | $d$ yr$^{-1}$ |
| $dM/dt$ | $2.741 \times 10^{-7}$ | $M_\odot$ yr$^{-1}$ |
of 0.0062 d, rather than in a monotonic fashion. The increasing rate of the secular period was calculated to be $+5.65 \times 10^{-7}$ d yr$^{-1}$, which may be caused by mass transfer from the secondary component to the primary in the system with a rate of $\sim 2.74 \times 10^{-7} M_\odot$ yr$^{-1}$.

3. The sinusoidal variation can be interpreted as an LTT effect due to the existence of a circumbinary object. If the third companion is on the main sequence and its orbit is coplanar with the eclipsing pair ($i_3 = 81^\circ 8$), the mass of the circumbinary object is $M_3 = 0.23 M_\odot$, and its radius and temperature are calculated to be $R_3 = 0.24 R_\odot$ and $T_3 = 3022$ K, respectively, following the empirical relations from Southworth (2009). These correspond to a spectral type of about M6 V and a bolometric luminosity of $L_3 = 0.004 L_\odot$, and contribute $\sim 0.03\%$ to the total light of the triple system. It would thus be difficult to detect such a faint companion through analyses of spotted light curves and spectroscopic observations. The absence of evidence does not rule out the presence of the hypothetic third component.

4. The results presented in this paper indicate that BX Dra is an A-subtype overcontact binary with an unseen circumbinary object; the more massive primary star has a spectral type of F0 and the secondary component a spectral type of F1–2. We think that the hot spot on the primary star could be produced as a result of the impact of the gas stream from the less-massive secondary star. The higher mass-transfer rate than the other overcontact systems, and no variation of spot parameters for about four years, support this hot spot model. Moreover, because both components should not have deep convective envelopes, as surmised from their temperatures, it is unreasonable to imagine that magnetic spots on the components of the system are the main cause of the light variation.

Although all historical timings of BX Dra are in agreement with the calculated LTT effect, as can be seen in figure 5, because of the absence of any independent third-body detection, we consider the possibility that a magnetic activity cycle may be the main cause of the sinusoidal period modulation (Applegate 1992; Lanza et al. 1998). With the period ($P_3$) and amplitudes ($K$) listed in table 7, the model parameters were calculated for each component from the Applegate formulae.
Table 8. Minimum timings determined by the W–D code from individual eclipses of BX Dra.

| Observed*a,† | W–D‡ | Error§ | Difference§ | Filter | Min | Reference |
|--------------|-------|--------|-------------|--------|-----|-----------|
| 3758.6891    | 3758.6907 | ±0.00023 | ±0.00000 | BV | II | SGG |
| 3767.6644    | 3767.66375 | ±0.00015 | +0.00067 | BV | I | SGG |
| 3772.5851    | 3772.58546 | ±0.00022 | −0.00041 | BV | II | SGG |
| 3774.6127    | 3774.61214 | ±0.00016 | +0.00056 | BV | I | SGG |
| 3794.5882    | 3794.58853 | ±0.00014 | −0.00032 | I | II | SGG |
| 3800.6687    | 3800.66844 | ±0.00013 | +0.00029 | I | I | SGG |
| 3803.5635    | 3803.56325 | ±0.00007 | +0.00023 | I | I | SGG |
| 3905.4719    | 3905.47111 | ±0.00011 | +0.00075 | BVR | I | ZOLA |
| 3907.4969    | 3907.49692 | ±0.00014 | 0.00000 | BVR | I | ZOLA |
| 4575.1205    | 4575.12128 | ±0.00047 | −0.00078 | BV | II | KIM |
| 4581.2027    | 4581.20221 | ±0.00042 | +0.00049 | BV | I | KIM |
| 4584.0982    | 4584.09820 | ±0.00047 | 0.00000 | BV | I | KIM |
| 4586.1232    | 4586.12320 | ±0.00076 | 0.00000 | BV | II | KIM |
| 4588.1501    | 4588.14872 | ±0.00053 | +0.00138 | BV | I | KIM |
| 4603.2050    | 4603.20341 | ±0.00055 | +0.00159 | BV | I | KIM |
| 4685.1390    | 4685.13900 | ±0.00047 | 0.00000 | BV | II | KIM |
| 4686.0070    | 4686.00700 | ±0.00070 | 0.00000 | BV | I | KIM |
| 4931.2241    | 4931.22464 | ±0.00028 | −0.00051 | BVR | II | This article |
| 4932.0935    | 4932.09287 | ±0.00018 | +0.00065 | BVR | I | This article |
| 4934.1202    | 4934.12040 | ±0.00014 | −0.00019 | BVR | II | This article |
| 4951.2017    | 4951.20127 | ±0.00018 | +0.00047 | BVR | I | This article |
| 5314.2540    | 5314.25309 | ±0.00017 | +0.00089 | BVR | I | This article |
| 5327.2826    | 5327.28296 | ±0.00018 | −0.00032 | BVR | II | This article |
| 5332.2046    | 5332.20401 | ±0.00009 | +0.00056 | BVR | I | This article |
| 5337.1261    | 5337.12605 | ±0.00018 | 0.00000 | BVR | II | This article |
| 5350.1545    | 5350.15382 | ±0.00011 | +0.00063 | BVR | I | This article |
| 5352.1809    | 5352.18145 | ±0.00012 | −0.00058 | BVR | II | This article |
| 5353.0485    | 5353.04813 | ±0.00013 | +0.00033 | BVR | I | This article |
| 5354.2074    | 5354.20687 | ±0.00020 | +0.00056 | BVR | I | This article |

* Table 6.
† HJD 2450000 is suppressed.
‡ Uncertainties yielded by the W–D code.
§ Differences between columns (1) and (2).

Table 9. Aggregiate parameters for possible magnetic activity of BX Dra.

| Parameter | Primary | Secondary | Units |
|-----------|---------|-----------|-------|
| ΔP        | 0.1753  | 0.1753    | s     |
| ΔP/P      | 3.50 × 10⁻⁶ | 3.50 × 10⁻⁶ |       |
| ΔQ        | 1.28 × 10⁻⁵ | 3.70 × 10⁻⁶ | g cm² |
| ΔJ        | 2.60 × 10⁻⁷ | 1.00 × 10⁻⁷ | g cm² s⁻¹ |
| Iσ        | 6.05 × 10⁻⁴ | 6.30 × 10⁻⁵ | g cm² |
| ΔΩ        | 4.30 × 10⁻⁸ | 1.58 × 10⁻⁷ | s⁻¹ |
| ΔΩ/Ω      | 3.42 × 10⁻⁴ | 1.26 × 10⁻³ |       |
| ΔE        | 2.24 × 10⁻⁸ | 3.15 × 10⁻⁸ | erg   |
| ΔLrms     | 7.37 × 10⁻¹  | 1.04 × 10⁻¹  | erg s⁻¹ |
|          | 0.0192 | 0.0271   | L⊙   |
|          | 0.0020 | 0.0089   | L₁₂  |
| Δmrms     | ±0.0016 | ±0.0023  | mag  |
| B         | 4.1    | 5.4      | kG    |

The parameters are listed in table 9, where the rms luminosity changes (Δm_rms) converted to the magnitude scale were obtained with equation (4) in a paper of Kim et al. (1997). The variations of the gravitational quadrupole moment (ΔQ) are two orders of magnitude smaller than typical values of 10⁻³¹ to 10⁻²² for close binaries (Lanza & Rodono 1999). In reality, the magnetic mechanism is adequate for systems with a spectral type later than about F5 (Hall 1989), unlike the case of BX Dra. Moreover, it is difficult to produce perfectly smooth and tilted periodic components in the O–C variation using this model. At present, because there is no alternative, but the LTT effect, the sinusoidal variation most likely arises from an unseen third companion gravitationally bound to the eclipsing binary. The circumbinary object in BX Dra may have played an important role in the formation of the eclipsing pair, which would finally evolve into single star by angular-momentum loss through magnetic braking. Future high-precision timing measurements will be crucial in unveiling the orbital period change of this system.
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