The Orbital Period of HDE226868/Cyg X-1

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ABSTRACT

We present epoch 1996, high-quality radial velocity data for HDE 226868, the optical counterpart of Cygnus X-1. Combining our results with all published historical data, we have derived a new ephemeris for the system of HJD2450235.29 + n × 5.5998, which allows accurate orbital phase calculations to be made for any X-ray observations over the last 30 years. We find no evidence for any period change as has been suggested by Ninkov, Walker \& Yang (1987). We discuss the shortcomings of previous work in establishing the period and orbital elements.

Key words: X-rays: stars \–\ binaries: close \–\ stars: individual: Cyg X-1 \–\ accretion, accretion discs

1 INTRODUCTION

Cygnus X-1, identified with the bright (V\textasciitilde8) star HDE226868 (Bolton 1972; Webster \& Murdin 1972), has long been regarded as the best black hole candidate among the high-mass X-ray binaries. As such, it has been an object of extensive observation over the past two and a half decades. Perhaps surprisingly, there remain some important uncertainties and discrepancies in the derived properties of the system. In particular, Ninkov, Walker, \& Yang (1987, hereafter NWY) report evidence of possible period variation, discussed below, and additional periodicities on timescales ranging from 39 days to 4.5 years have been suggested by Kemp, Herman, \& Barbour (1978), Wilson and Fox (1981), Friedhorsky, Terrell, \& Holt (1983), and Walker and Quintanilla (1978).

HDE226868 is a single-lined spectroscopic binary. The optical spectrum has been classified O9.7Iab by Walborn (1973), with variable emission at HeII \(\lambda\) 4686 and, less prominently, at the Balmer lines. The radial velocity period of 5.6 days has been established for over two decades, and the definitive orbital elements and ephemeris were published by Gies and Bolton (1982, hereafter GB). They give a period of 5.5974 ± 0.00008 days, a precision which translates to an uncertainty of only ±0.02 cycle in phase at the present time.

However, NWY, in a subsequent radial-velocity study, reported a somewhat longer period of 5.6017 ± 0.0001 days, and suggest the possibility of a period increase with time.

These results have the effect that the orbital phase of the Cyg X-1 system is then highly uncertain at the present epoch. The phase calculated using the ephemeris of NWY differs from the GB phase by 0.5 cycle, and if the period is in fact varying, the phase at the present epoch is completely indeterminate.

If correct, a time-varying period would have important implications for the mass transfer rate and hence evolution of the binary. Furthermore, with this indeterminacy in phase, it is impossible to ascribe and interpret accurately features in the X-ray light curve such as the dipping behaviour, in particular the distribution of dipping with orbital phase (e.g. Remillard and Canizares 1984). To resolve these ambiguities we therefore undertook a program of observations to re-establish the orbital ephemeris of HDE226868. These data also allowed us to undertake a more detailed investigation of the long-term stability of the orbit, as high quality data now exist over a ~30 year baseline. Our new ephemeris has thereby allowed us to complete a survey of the distribution of X-ray dipping with orbital phase (Balucinska-Church et al. 1998).

2 OBSERVATIONS

Through the La Palma Service Programme, and with the assistance of regularly scheduled observers, we obtained CCD spectra of HDE226868 using the Intermediate Dispersion Spectrograph on the Isaac Newton Telescope on 17 nights.
in May and June 1996. These included 11 consecutive nights covering two complete orbital cycles. In all we obtained 37 spectra of the object, each covering a spectral range of 4100 to 4900Å, with a dispersion of approximately 0.8 Å/pixel. Exposures varied from 100 to 200 seconds, and yielded a S/N in excess of 100. In addition, we observed 19 Cep, a radial velocity standard of similar spectral type, on two nights, for reference and calibration purposes.

The spectra were extracted and reduced using standard IRAF routines. The extracted spectra were wavelength calibrated using a Cu-Ar arc recorded immediately before and after the program spectra, and then normalized. Our wavelength calibration accuracy had rms residuals of ~0.10Å. Typical HDE226868 and 19 Cep spectra are shown in Figure 1.

3 PERIOD DETERMINATION

We determined radial velocities by cross-correlation of the HDE226868 spectra with the 19 Cep spectra, using IRAF routines. Separate determinations were made for the hydrogen and helium lines. We used the HeI absorption lines at 4388, 4472, 4713 and 4921Å. The resulting velocities are given in Table 1, and were reduced to heliocentric velocities using the catalogue value (Hoffleit 1982) for the radial velocity of 19 Cep. We performed period searches on both sets of velocities, as well as on our velocities in combination with previously determined velocities from the literature. We used several different period-search techniques, including Scargle periodograms, Fourier searches, and chi-square minimization to a circular orbit fit. All methods yielded similar results, as follows.

The best fit period to the hydrogen line velocities for our data alone is 5.566 ± 0.012 days, while the best fit to our helium line data is 5.629 ± 0.015 days. The apparent discrepancy here is startling, as is the amount of apparent change in period from the canonical value in either case. Both of these issues can be readily resolved.

It is well established that the hydrogen lines are contaminated by emission whose velocity is in approximate antiphase with the absorption lines (GB; Hutchings, Crampston, & Bolton 1979). This produces variable and irregular line profiles which yield spurious velocities and periods when cross-correlated with standard spectra. So any period determined from the hydrogen line velocities is highly suspect. For this reason we reject all velocity determinations based on the hydrogen lines, and in working with historical data below, we use only published velocities determined for the helium lines.

The fact that the best-fit period to the helium lines seems to be 2σ larger than previously determined values should also be viewed with some scepticism. In fact, with a dense grid of observations over a relatively short period of time, the quality of fit is good over a much broader period range than suggested by the quoted uncertainty. Fitting our data to the NWY period, or to the GB period, produces χ² residuals which are not significantly worse than those for our best fit. In fact, the formal uncertainty calculated by the fitting routines is undoubtedly too small; this is because the scatter of the data is such that even for the best orbital models the resulting χ² is too large for the formal uncertainty calculations to be valid. We shall see below that this is not unique to our results but in fact has been a problem for most, and perhaps all, previous published orbital solutions for Cyg X-1; uncertainties have been systematically underestimated, resulting in apparent discrepancies where none really exist.

To test for the possibility of period variation, we combined our observations with all previously published helium-line velocity data (Brucato and Zappala 1974; GB; NWY) and performed a χ² minimization weighted fit to a circular orbit both with a fixed period and with a period which varies linearly with time, using the MINUIT package of function-fitting routines (James 1994). The results are summarized in Table 2 and plotted in Figure 1. The best fixed period is 5.5998 ± 0.0001 days, with a χ² of 4284; the best variable period is 5.5997 ± 0.0001 days, with P of 3.8 × 10⁻⁷ and χ² of 4231. But with only 216 data points, this means that the χ² is ~20 in both cases. Our new period agrees well with the photometric period derived recently by Voloshina, Lyutyi & Tarasov (1997) and a solution from HeI λ6678 measurements by Sowers et al (1998). Our values for γ and K are within 2σ of previous results (NWY and GB).

The variable-period model produces a slightly better fit to the data, but, again, with a χ² difference of less than 1.5%, the improvement in quality of fit between that and the fixed-period model is not statistically significant. We conclude that there is no compelling evidence for period variation in Cygnus X-1. We have therefore adopted the orbital elements of the best-fit constant period model in all further discussion.

We computed O–C residuals for all the helium-line velocities and performed period searches on these. No significant periodicity was found in these residuals. In particular, we find no evidence of the suggested periodicities at 39d (Kemp, Herman, & Barbour 1978), or 4.5 years (Wilson and Fox 1981) or of the 294 day X-ray modulation (Priedhorsky, Terrell, & Holt 1983) or the 91d photometric period (Walker and Quintanailla 1978). The absence of a 294 d signal was also noted by Gies & Bolton (1984).

4 DISCUSSION

Our best-fit period for the combined datasets, 5.5998 ± 0.0001 d is identical to well within the standard errors with the GB period of 5.59974 ± 0.00008 d, and our T₀, or epoch of inferior conjunction, agrees with the prediction of the GB ephemeris to within 0.014 phase, or 0.078 d. Since the uncertainty in the periods yields an uncertainty in the GB prediction of T₀ of ± 0.12 days at this epoch, this is excellent agreement. Thus our results confirm the ephemeris of GB and refute suggestions of period variation by NWY.
Why, then, did NWY’s result show such a discrepancy and suggest a change in period? They reported that the period determined from their data alone was $5.60172 \pm 0.00003$ d, differing by $20 \sigma$ from the period determined from all previous observations. We suggest several sources for this error.

First of all, we performed our own period searches on the data published by NWY; the best fit we find is at $5.6002 \pm 0.0003$ d, or only $2 \sigma$ greater than the GB value, so we may be looking at much ado about a typographical error. In addition, there is excellent phase agreement between the NWY data and the GB ephemeris, again suggesting no real period discrepancy.

Finally, it seems that the error estimates for both the NWY period and their period determined from historical data are too small by as much as an order of magnitude. This is primarily because the formal error calculations used to determine these error estimates are based on the assumption of a very good fit of the model to the data, i.e. that $\chi^2 \sim 1$. This condition is not met by any of the data sets and fits used in this work, presumably because the estimates of the uncertainties in the velocities were too small, although perhaps because of variability in the source. We recalculated the fits, trying larger estimates for the velocity uncertainties until the reduced chi-square criterion was satisfied. We found that the period uncertainties then were about an order of magnitude larger than reported by the original authors. For example, treating NWY’s data in this way yields a best-fit period of $5.6002 \pm 0.0003$ d, and the discrepancy with GB disappears.

An additional source of underestimated error uncertainty is the inclusion by both NWY and Bolton (1975) of two velocities obtained by Seyfert and Popper (1941), ostensibly to improve the precision of the period determinations. For example, Bolton (1975) uses these points to decrease his uncertainty estimate by a factor of 10; NWY do not discuss the effect of including these points on their uncertainty. Popper (1996, personal communication) suggests that these velocities are “very weak reeds on which to hang significant conclusions”, the velocities having considerable uncertainty. Popper (1996, personal communication) suggests that these velocities are “very weak reeds on which to hang significant conclusions”, the velocities having considerable uncertainty. Popper (1996, personal communication) suggests that these velocities are “very weak reeds on which to hang significant conclusions”, the velocities having considerable uncertainty. Popper (1996, personal communication) suggests that these velocities are “very weak reeds on which to hang significant conclusions”, the velocities having considerable uncertainty. Popper (1996, personal communication) suggests that these velocities are “very weak reeds on which to hang significant conclusions”, the velocities having considerable uncertainty.

GB also introduced “velocity corrections” to many of their velocities, shifting spectra to fit a mean interstellar K-line velocity due to instabilities in their spectograph. It is not unlikely that this introduced uncertainties larger than the mean errors they report.

5 CONCLUSIONS

We have carried out a programme of radial velocity determinations for the black hole binary Cyg X-1, and have combined these data with data used previously to determine the period, to provide a new orbital ephemeris for the source. A critical consideration of the errors associated with previous work has shown these to be underestimated. Based on this, our main conclusion is that there is no evidence for a change in orbital period as suggested by Ninkov et al. Finally, our new ephemeris allows the orbital phase calculation for Cyg X-1 with an error that is much reduced compared with the error that would be attached to extrapolating the Gies and Bolton ephemeris with its quoted accuracy to the present epoch.

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Figure 1: Typical rectified spectra of HDE226868 (top) and the radial velocity standard 19 Cep (bottom) obtained with the La Palma 2.5 m INT. The spectral types are very similar, but note the HeII λ4686 emission in HDE226868.
Table 1. Radial Velocity Data for HDE226868.

| Julian Date 2450000+ | Helio-centric Phase | Hydrogen Lines | Helium Lines | 0 - C |
|----------------------|---------------------|----------------|-------------|-------|
|                      | ν_r                 | σ_v           | ν_r         | σ_v   |
| 228.739              | 0.830               | -71.6         | 6.8         | -54.4 | 5.2  | 17.1 |
| 228.742              | 0.831               | -74.8         | 7.2         | -59.0 | 5.3  | 12.3 |
| 228.744              | 0.831               | -75.5         | 7.5         | -56.2 | 5.8  | 15.1 |
| 229.715              | 0.004               | -5.6          | 6.6         | 12.4  | 7.0  | 17.8 |
| 229.724              | 0.006               | -7.6          | 6.6         | 10.3  | 6.1  | 12.8 |
| 230.731              | 0.185               | 73.7          | 7.1         | 86.2  | 5.6  | 23.1 |
| 230.733              | 0.186               | 69.5          | 6.9         | 88.0  | 5.5  | 24.0 |
| 231.736              | 0.365               | 55.6          | 5.0         | 64.9  | 4.4  | 13.7 |
| 231.738              | 0.366               | 52.8          | 4.8         | 61.8  | 4.4  | 10.9 |
| 232.736              | 0.544               | -33.8         | 6.9         | -34.2 | 5.8  | -8.2 |
| 232.738              | 0.544               | -35.9         | 6.4         | -36.9 | 5.8  | -10.9|
| 233.723              | 0.720               | -75.2         | 7.0         | -64.6 | 3.9  | 14.9 |
| 233.726              | 0.721               | -80.7         | 7.2         | -68.8 | 4.5  | 10.8 |
| 234.730              | 0.900               | -53.2         | 6.0         | -43.7 | 5.0  | 6.2  |
| 234.733              | 0.901               | -52.4         | 6.0         | -39.9 | 5.3  | 9.4  |
| 235.726              | 0.078               | 25.1          | 7.2         | 47.4  | 4.1  | 17.3 |
| 235.730              | 0.079               | 26.6          | 7.1         | 46.5  | 5.0  | 15.9 |
| 236.737              | 0.258               | 69.3          | 7.1         | 80.6  | 6.9  | 10.7 |
| 236.740              | 0.259               | 68.7          | 6.8         | 77.0  | 7.3  | 6.7  |
| 237.738              | 0.437               | 12.0          | 7.9         | 7.4   | 5.6  | -16.3|
| 238.745              | 0.617               | -64.5         | 5.5         | -60.6 | 3.4  | -4.6 |
| 238.746              | 0.617               | -69.0         | 7.0         | -65.2 | 4.2  | 0.0  |
| 238.748              | 0.618               | -71.4         | 6.9         | -75.4 | 5.2  | -19.1|
| 241.722              | 0.149               | 51.4          | 5.5         | 60.8  | 4.0  | 5.4  |
| 242.704              | 0.324               | 54.8          | 5.3         | 60.0  | 4.0  | -2.1 |
| 242.705              | 0.324               | 56.7          | 5.9         | 61.6  | 3.4  | -0.5 |
| 243.721              | 0.506               | -2.8          | 5.4         | 2.9   | 4.9  | 11.1 |
| 243.722              | 0.506               | -4.9          | 5.0         | -7.8  | 2.8  | 0.4  |
| 253.726              | 0.292               | 72.0          | 9.8         | 49.5  | 5.9  | -17.9|
| 253.727              | 0.292               | 74.2          | 10.2        | 44.1  | 5.4  | -23.4|
| 254.721              | 0.470               | 8.4           | 9.9         | -7.3  | 6.3  | -16.0|
| 254.721              | 0.470               | 12.0          | 10.3        | -7.9  | 6.3  | -16.6|
| 255.673              | 0.640               | -64.6         | 6.3         | -70.6 | 5.0  | -7.1 |
| 255.674              | 0.640               | -63.2         | 6.3         | -67.0 | 6.5  | -3.5 |
| 255.675              | 0.640               | -68.0         | 5.9         | -71.1 | 4.9  | -7.5 |

Table 2. Orbital Solutions for HDE226868.

| Variable Period Model | Fixed Period Model |
|-----------------------|--------------------|
| P0 (days)             | 5.5997(1)          | 5.5998(1)        |
| P                    | 3.8(4) X 10^{-7}   | 0 (fixed)        |
| T0 (JD 2,440,000+)    | 1869.10(5)         | 10235.29(1)      |
| γ (km s^{-1})        | -5.4(1)            | -5.4(1)          |
| K (km s^{-1})        | 75.53(15)          | 75.48(15)        |
| χ^2                  | 4231               | 4283             |

Figure in parentheses is uncertainty in last digit.

Figure 2: Best fitting fixed period, circular orbit to all helium radial velocity data (ours plus all previously published material, see text). The lower panel shows the residuals to the fit.
