THE ORBITAL PERIOD OF THE ULTRACOMPACT LOW-MASS X-RAY BINARY 4U 1543–624

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ABSTRACT

We report the discovery of the orbital period of the ultracompact low-mass X-ray binary (LMXB) 4U 1543–624

using time-resolved optical photometry taken with the 6.5-m Clay (Magellan II) telescope in Chile. The light

curve in the Sloan $r'$ band clearly shows a periodic, sinusoidal modulation at 18.2±0.1 min with a fractional

semi-amplitude of 8%, which we identify as the binary period. This is the second shortest orbital period among

all the known LMXBs, and it verifies the earlier suggestion of 4U 1543–624 as an ultracompact binary based on

X-ray spectroscopic properties. The sinusoidal shape of the optical modulation suggests that it arises from X-ray

heating of the mass donor in a low-inclination binary, although it could also be a superhump oscillation in which

case the orbital period is slightly shorter. If the donor is a C-O white dwarf as previously suggested, its likely mass

and radius are around 0.03 $M_\odot$ and 0.03 $R_\odot$, respectively. For mass transfer onto a neutron star and driven by

gravitational radiation, this implies an X-ray luminosity of $6.5 \times 10^{36}$ erg s$^{-1}$ and a source distance of ≈7 kpc.

We also discuss optical photometry of another LMXB, the candidate ultracompact binary 4U 1822–000. We detected

significant optical variability on a time scale of about 90 min, but it is not yet clear whether this was due to a

periodic modulation.

Subject headings: binaries: close — stars: individual (4U 1543–624, 4U 1822–000) — X-rays: binaries — stars:

— low mass — stars: neutron

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) containing ordinary, hydrogen-rich mass donors have a minimum orbital period

around 80 min (Paczyński & Sienkiewicz 1981; Rappaport, Joss, & Webbink 1982). However, systems with hydrogen-poor

or degenerate donors can evolve to extraordinarily small binary separations, with orbital periods as short as a few minutes (Nel-

son, Rappaport, & Joss 1986). These so-called ultracompact binaries include three X-ray bursters (two in globular clusters),
a classical X-ray pulsar, and three millisecond X-ray pulsars, spanning a range of orbital periods from 11 to 50 minutes. Be-
sides these accreting neutron stars, there is also a related class among the accreting white dwarfs, the AM CVn binaries (see
Warner 1995). Together, these systems represent extreme and exotic endpoints in binary and stellar evolution (see, e.g., Pod-
siadlowski, Rappaport, & Pfahl 2002). In all cases, the donor stars in these systems must have extremely low mass and be
either hydrogen-depleted or degenerate (Nelson, Rappaport, & Joss 1986; Yuengelson, Nelemans, & van den Heuvel 2002).

Although these systems had initially been assumed to be relatively rare, the number known has doubled in the past few years.

In addition, recent X-ray spectroscopic work has identified several more candidate ultracompact binaries on the basis of

comparison to the known ultracompact LMXB 4U 1626–67, with low-mass, Ne-enriched C-O white dwarfs suggested as possible donors (Juett, Psaltis, & Chakrabarty 2001; Juett & Chakrabarty 2003). Candidates may also be identified through an unusually low optical—X-ray flux ratio (Deuchter, Margon, & Anderson 2000). In an effort to verify these proposed candidates, we have recently undertaken a systematic optical survey aiming to detect orbital flux modulations through time-
resolved photometry. We report on the first results of our survey in this paper with observations of the LMXBs 4U 1543–624

and 4U 1822–000.

These two sources were discovered by the Uhuru mission over thirty years ago (Giacconi et al. 1972). Both are presumed to

be accreting neutron stars, although the absence of either X-ray bursts or pulsations precludes a definitive conclusion. The

source 4U 1543–624 ($l = 322^\circ$, $b = -6^\circ$) has since been extensively observed by a series of X-ray missions (Singh, Appa-
rao, & Kraft 1994; Christian & Swank 1997; Asai et al. 2000; Schultz 2003; Farinelli et al. 2003; Juett & Chakrabarty 2003).

It was identified as a candidate ultracompact system by Juett et al. (2001), but observations with the Chandra X-Ray Observa-
tory and XMM-Newton found no evidence for orbital modulation of the X-ray flux (Juett & Chakrabarty 2003). The B ≳ 20

optical counterpart of 4U 1543–624 was identified by McClintock et al. (1978) based on its SAS-3 position, which has been

subsequently verified by Chandra (Juett & Chakrabarty 2003). Optical spectra show no lines of H or He and support the sug-
gestion of C-O white dwarf donor (Nelemans et al. 2004; Wang & Chakrabarty 2004). The X-ray source 4U 1822–000 ($l = 30^\circ$,
b = +6$^\circ$) has been less well studied. Its $V = 22$ optical counterpart was identified by Chevalier & Ilovaisky (1985). Chandra

observations verify that the X-ray source is coincident with the optical position and show no evidence for orbital modulation of

the X-ray flux (Juett & Chakrabarty 2004). We identified the system as a candidate ultracompact system on the basis of

its optical/X-ray flux ratio. In this paper, we report the detection of an 18.2-minute periodicity in the optical flux from

4U 1543–624 and the presence of significant variability in the optical flux from 4U 1822–000.

2. OBSERVATIONS AND DATA REDUCTION

Our optical photometric observations were made on 2003 August 2–4 using the 6.5-meter Clay/Magellan II telescope at
Las Campanas Observatory in Chile. The detector was the Raymond and Beverly Sackler Magellan Instant Camera (MagIC), a 2048×2048 pixel CCD camera providing a 0.
\(\text{"} 0.069\) pixel\(^{-1}\) plate scale and a 142\(\text{"} 0\) field of view at the f/11 focus of the telescope. A Sloan \(r'\) filter (Fukugita et al. 1996) was used for our obser-
vations. The total observation time spanned approximately 100
min on August 2 for 4U 1822
\(-\)000 with 99 CCD image frames
taken, and 140 min on August 3 for 4U
1543
\(-\)624 with 137 frames taken. The exposure time of each in-
dividual frame was 30 seconds for both targets. Since the read-
out time of MagIC is 20 seconds, we obtained approximately
one image per minute over the course of our observations. The
telescope position was dithered 5
\(\text{"} 0\) once every 20 minutes dur-
ing the observations. The conditions during our observations
on August 2 were excellent, with the 0.
\(\text{"} 6\) seeing. On August 3,
the conditions were windy, with the seeing varying in a range
of 0.
\(\text{"} 6\)–1
\(\text{"} 0\). In addition to our science targets, the Sloan photo-
metric standard star G 93-48 (Smith et al. 2002) was observed
on August 3 for flux calibration of 4U 1543
\(-\)624. A few images
of both science targets were obtained on August 4, allowing us
to extend our photometric calibration to 4U 1822
\(-\)000 as well.

In Figure 1, we show finder images of our two fields.

We used the IRAF analysis package for our initial data re-
duction, including bias subtraction and flat fielding. We then
used DOHPOT (Schechter, Mateo, & Saha 1993), a point-spread

\section*{3. RESULTS}

The light curve for 4U 1543
\(-\)624 is shown in the top panel of
Figure 2. The average magnitude was \(r' = 20.42 \pm 0.03\). How-
ever, a periodic modulation with a semiamplitude of around
0.1 magnitudes is also clearly visible. For comparison, the
light curve of a check star of similar brightness in the same
field is also shown. The standard deviation of the brightness
of this check star is only 0.026 magnitudes, which shows that
the light curve variation of our target is highly significant. We
made an initial estimate of the modulation period by interpo-
larating the data into an evenly-sampled time series and using
the epoch-folding search technique on the uninterpolated
data (Leahy et al. 1983) to determine the period of
18.2
\(\pm\)0.1 minutes. A plot of the data folded on this period is
shown in Figure 3, along with the best-fit sinusoid with a semi-
amplitude of 0.081
\(\pm\)0.002 magnitudes. The topocentric time
of phase zero (maximum brightness) was UT 2003 August 3
00:44:20, corresponding to August 3 00:48:32 (TDB) at the so-
lar system barycenter, with an uncertainty of 66 seconds.

In the bottom panel of Figure 2, we show the light curve of
4U 1822
\(-\)000. The average magnitude was \(r' = 21.58 \pm 0.08\). How-
ever, the target brightness is clearly varying systematically
by a few tenths of a magnitude over the 100 min observation.
These changes are quite significant compared to the 0.027 mag-
nitude scatter observed in nearby check star. The variability
could possibly be due to a ∼90 min periodicity, but our data span is insufficient to determine this.

![Image](image_url)

**Fig. 3.** — The $r'$ band photometric data for 4U 1543–624 folded on the 18.2 min period. Phase zero is chosen to be of maximum brightness. Two cycles are displayed for clarity. The best fitting sinusoid is plotted as the solid curve.

### 4. Discussion

We have found an 18.2 min periodicity in the optical light curve of 4U 1543–624. Since the modulation appears to be coherent, this is almost certainly the orbital period of the binary, verifying its ultracompact nature. This is the second shortest orbital period for an LMXB, after the 11-minute binary 4U 1820–30 (Stella, Friedhorsky, & White 1987). We note that this discovery bolsters the earlier suggestion of 4U 0614+091 and 2S 0918–549 as ultracompact binaries on the basis of X-ray and optical evidence (Juett et al. 2001; Juett & Chakrabarty 2003; Nelemans et al. 2004; Wang & Chakrabarty 2004).

Sinusoidal modulation of the optical light curve for LMXBs generally arises from X-ray heating of the companion star by the central X-ray source in a relatively low-inclination binary (see van Paradijs & McClintock 1995), with the visible area of the heated face varying as a function of orbital phase, and the superior conjunction of the companion star corresponding to the observed brightness maximum of the light curve. For sufficiently low binary inclinations, blockage by the accretion disk does not occur, resulting in a sinusoidal profile. A possible alternative explanation is that the 18.2 min variation is a superhump oscillation (see Warner 1995 for a review). Superhumps are observed as optical photometric modulations in cataclysmic variables and LMXBs at periods a few percent longer than the binary period. These oscillations, which only occur in binaries with extreme mass ratios (like ultracompact binaries), are understood to arise because of an orbital resonance condition that leads to a precessing, eccentric accretion disk (Whitehurst & King 1991; Lubow 1991). Without an independent determination of the binary period from, e.g., X-ray variability or Doppler line measurements, we cannot definitively distinguish between these possibilities. In either case, however, 4U 1543–624 certainly has an orbital period around 18 min.

As an ultracompact binary, 4U 1543–624 must contain a hydrogen-depleted or degenerate donor resulting from the evolution of either an evolved main-sequence star+neutron star binary or a white dwarf+neutron star binary (see Nelson & Rappaport 2003 and references therein for a recent discussion of evolutionary scenarios for ultracompact binaries). Indeed, based on both X-ray (Juett et al. 2001; Juett & Chakrabarty 2003) and optical measurements (Nelemans et al. 2004; Wang & Chakrabarty 2004), it has been suggested that the donor is a low-mass C-O white dwarf. If so, we can use our orbital period measurement to estimate the mass and radius of the donor. Since the mean density of a Roche-lobe–filling companion is determined by the binary period, our 18 min period defines a mass-radius relation for the companion, shown as the solid curve in Figure 4. (In the absence of measured mass function for the binary, the allowed curve extends down to $M_2 = 0$.) In comparing this to stellar models, we note that recent studies of three millisecond pulsars in ultracompact LMXBs have shown that the extremely low-mass white dwarf donors in such systems may be thermally bloated compared to cold stars, affecting their $M$-$R$ relation (Bildsten 2000; Deloye & Bildsten 2003). For comparison, Figure 4 also shows both cold and hot solutions for pure C and O white dwarfs from the models of Deloye & Bildsten (2003). For a Roche–lobe-filling donor, a mass in the 0.025–0.03 $M_⊙$ range and a radius around 0.03 $R_⊙$ is indicated. Since mass transfer in an ultracompact binary is driven by gravitational radiation, this mass estimate implies a mass transfer rate of

$$M \approx 5.5 \times 10^{-10} M_⊙ \text{ yr}^{-1} \left( \frac{M_1}{1.4 M_⊙} \right)^{2/3} \times \left( \frac{M_2}{0.03 M_⊙} \right)^2 \times \left( \frac{P_{\text{orb}}}{18.2 \text{ min}} \right)^{-8/3},$$

where $M_1$ is the mass of the compact primary, $M_2$ is the mass of the white dwarf donor, and $P_{\text{orb}}$ is the binary period. Given the measured unabsorbed 0.5–10 keV X-ray flux of ∼1 × 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$ (Juett & Chakrabarty 2003), this suggests a source distance of ∼7 kpc.

![Image](image_url)

**Fig. 4.** — Mass-radius constraints for the companion star in 4U 1543–624. The solid curve is the $M$-$R$ relation for a Roche-lobe-filling donor in an 18.2 min binary. Also shown are the model curves for low-mass carbon (dashed lines) and oxygen (dot-dashed lines) white dwarfs for both cold (10$^6$ K) and hot (3×10$^6$ K) core temperatures, taken from Deloye & Bildsten (2003). The donor must have a mass in the 0.025–0.03 $M_⊙$ range with a radius around 0.03 $R_⊙$.

The ∼90 min optical variability of 4U 1822–000 is also suggestive of a periodicity, in which case it may also provide a binary period, but a considerably longer observation will be necessary to test this. Indeed, the variability might not be periodic at all, but could instead be only quasiperiodic or even...
stochastic. Strong ∼15 min optical/UV quasiperiodic oscillations were previously detected in the 42 min ultracompact LMXB 4U 1626−67 (Chakrabarty et al. 2001), showing that photometric variability in ultracompact binaries need not only occur near the orbital period. Again, only an observation long enough to contain many modulation cycles can distinguish between a periodic and a quasiperiodic oscillation (or stochastic variability) and allow a secure measurement of its time scale.

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