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A Tentative 114 minute Orbital Period Challenges the Ultracompact Nature of the X-Ray Binary 4U 1812–12

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Abstract

We present a detailed time-resolved photometric study of the ultracompact X-ray binary candidate 4U 1812–12. The multicolor light curves obtained with HiPERCAM on the 10.4 m Gran Telescopio Canarias show a ≃114 minute modulation similar to a superhump. Under this interpretation, this period should lie very close to the orbital period of the system. Contrary to what its other observational properties suggest (namely, persistent dim luminosity, low optical-to-X-ray flux ratio, and lack of hydrogen features in the optical spectrum), this implies that 4U 1812–12 is most likely not an ultracompact X-ray binary, which is usually defined as a system with an orbital period lower than 80 minutes. We discuss the nature of the system, showing that a scenario in which 4U 1812–12 is the progenitor of an ultracompact X-ray binary may reconcile all the observables.

Unified Astronomy Thesaurus concepts: Stellar accretion disks (1579); Low-mass x-ray binary stars (939); Neutron stars (1108)

1. Introduction

The ultracompact family of low-mass X-ray binaries (LMXBs) is composed of those systems in which a compact object, either a neutron star or a black hole, accretes material from an evolved, hydrogen-deficient companion star in a tight orbit with a period $P_{\rm orb} < 80$ minutes (Rappaport et al. 1982; Verbunt & van den Heuvel 1995). Three evolutionary channels, depending on the nature of the donor star, have been proposed to explain the origin of such compact systems: the white dwarf channel, the helium star channel, and the evolved main-sequence star channel (see, e.g., Nelemans et al. 2010; Heinke et al. 2013). Distinguishing between these formation paths is not always straightforward, since the final state of the donor is similar for the three scenarios. In this regard, the study of the progenitors of ultracompact systems (i.e., before the orbital period becomes shorter than 80 minutes) may be key to shed light on the origin of this family.

The neutron star LMXB 4U 1812–12 is a strong ultracompact candidate. Its persistently low X-ray luminosity ($\sim 4 \times 10^{35}$ erg s^{-1}) and low optical-to-X-ray flux ratio suggest that it harbors a small accretion disk (van Paradijs & McClintock 1994; Bassa et al. 2006; in 't Zand et al. 2007). In addition, its optical spectrum lacks hydrogen spectral features, which suggest a hydrogen-exhausted donor star (Armas Padilla et al. 2020).

In order to confirm the ultracompact nature of 4U 1812–12, we performed a detailed time-resolved photometric study using data taken with the HiPERCAM imager on the 10.4 m Gran Telescopio Canarias (GTC).

2. Observations and Reduction

We obtained images of 4U 1812–12 with HiPERCAM (Dhillon et al. 2021) on the GTC in La Palma. This high-speed camera uses four dichroic beamsplitters and five frame-transfer CCDs to simultaneously image the u_s, g_s, r_s, i_s, and z_s optical bands.[7] The CCD detectors were used in full-frame mode with slow readout and no binning. The observations presented here were taken on 2021 June 15 with an exposure time of 12.9 s (with only 8 ms dead time between exposures) for 1129 frames (∼4 hr total coverage). The cadence in the u_s and g_s bands was slower by a factor of 15 in an attempt to increase the signal-to-noise ratio (S/N) in these bands. The data were reduced using the HiPERCAM pipeline.[8] We block averaged the r_s, i_s, and z_s images and obtained 60 images per band with improved S/N. We then extracted the count rates of 4U 1812–12 and a comparison star[9] via variable aperture photometry by direct summing of the sky subtracted flux over the aperture, i.e., with no profile weighting. The S/Ns of the u_s and g_s images were insufficient to extract reliable fluxes. In fact, the source is not detected in either the u_s or g_s stacked images, so these bands are not discussed further in this Letter. The measured seeing gradually degraded during the last third of the observation from a median value in the z_s band of 1."1–1."8.

3. Period Analysis and Results

The light curves of 4U 1812–12 are shown in Figure 1. The average magnitudes of the system are $r_s = 23.17 \pm 0.02$, $i_s = 21.93 \pm 0.01$, and $z_s = 21.28 \pm 0.01$ mag. To compute

[7] HiPERCAM is equipped with "Super" SDSS filters, high-throughput versions of the SDSS filters, hence the "s" subscript.
[8] https://github.com/HiPERCAM/
[9] Gaia DR2 4153779729434598528, http://vizier.u-strasbg.fr/viz-bin/VizieR-S?Gaia%20DR2%204153779729434598528.

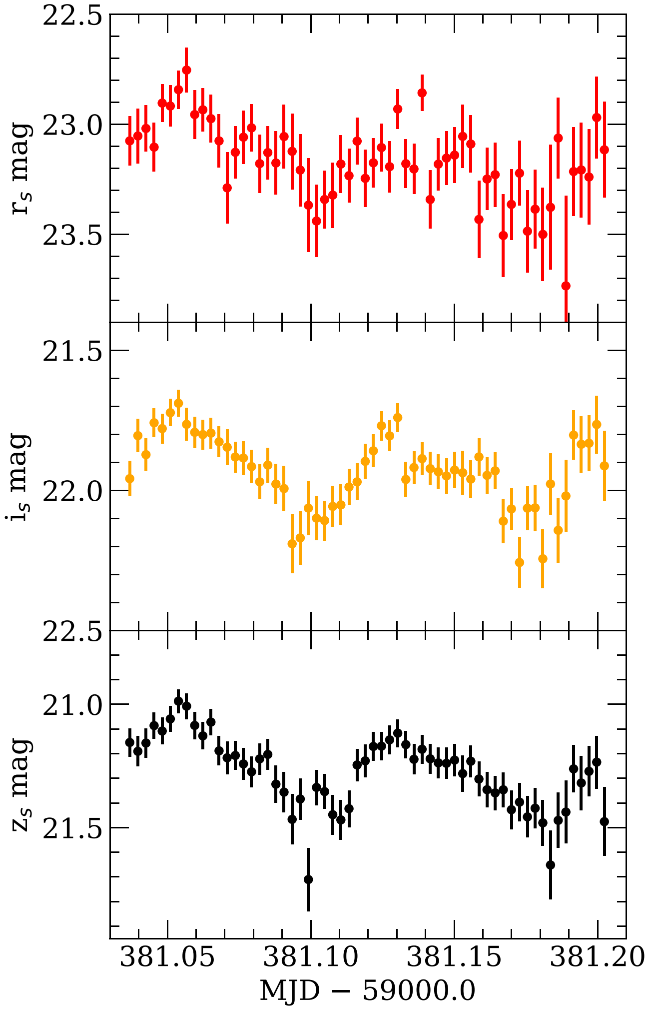

Figure 1. GTC/HiPERCAM $r_s i_s z_s$ light curves of 4U 1812–12. The individual images were block averaged into 60 bins prior to flux extraction to enhance the S/N.

the light curves we used the Pan-STARRS Data Release 1 mag of the comparison star $r = 20.33 \pm 0.02$, $i = 18.58 \pm 0.01$, and $z = 17.42 \pm 0.01$ mag.

We analyzed the z_s-band light curve of 4U 1812–12 using the analysis of variance (ANOVA) method (Schwarzenberg-Czerny 1996). This uses the ANOVA statistic, Θ, to assess the goodness of fits to the data with periodic orthogonal polynomials. The periodogram is displayed in Figure 2 and favors a period of 114.5 ± 3.5 minutes (0.0795 ± 0.0024 days), where the 1σ confidence interval was calculated using a postmortem analysis (Schwarzenberg-Czerny 1991) and is defined as the width of the periodogram peak at the mean noise power level (MNPL; $\Theta_{\rm MNPL} = 2.52$ in this case) in its vicinity. We also used the ANOVA method with the r_s and i_s light curves and obtained consistent results. In Figure 3 we show the average-subtracted light curves phase binned on this period. A peak-to-peak amplitude of ≈0.4 mag is found for the three bands.

The observed photometric modulation can be a reflection of the orbital period and may be produced by either X-ray irradiation of the donor star or a superhump with a period a few percent longer than the orbital period, caused by the precession of an eccentric accretion disk (van Paradijs et al. 1988; Whitehurst & King 1991). While X-ray heating of the donor produces sinusoidal light curves (e.g., van Paradijs & McClintock 1995), changes in the disk size and shape and resonance between the Keplerian orbits in the disk and the orbital motion of the donor star can produce a more complex morphology in the superhump modulations (O'Donoghue & Charles 1996; Haswell et al. 2001; Zurita et al. 2008).

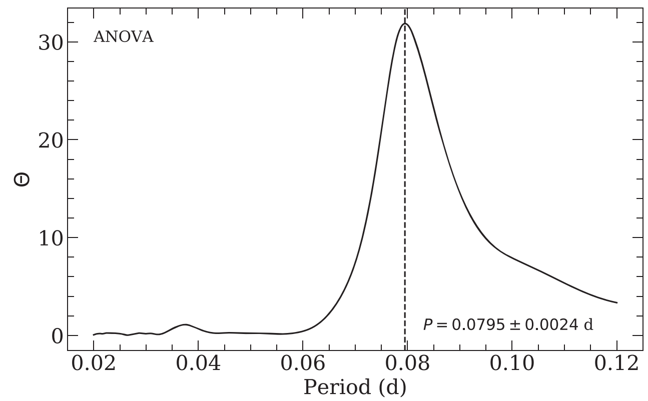

Figure 2. Analysis of variance (ANOVA) periodogram of the z_s-band light curve of 4U 1812–12. A period of 114.5 ± 3.5 minutes (0.0795 ± 0.0024 days) is favored.

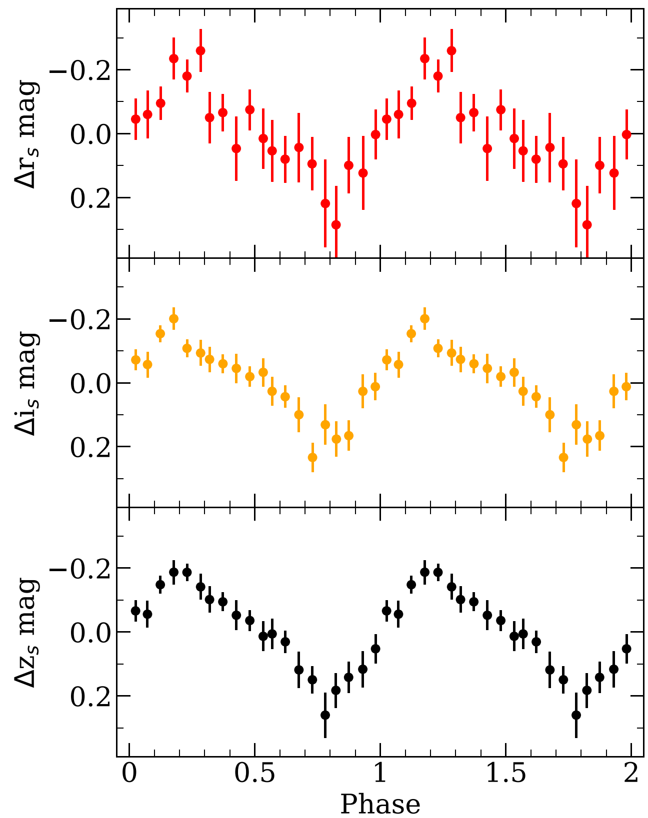

Figure 3. GTC/HiPERCAM $r_s i_s z_s$ light curves phase binned (20 bins) on the 114.5 ± 3.5 minute period, in which the respective average magnitudes have been subtracted. The phases are computed relative to the time of the first data point. Colors are the same as in Figure 1. The whole cycle has been plotted twice for continuity.

The sawtooth-like modulation that we detected (Figure 1) supports the superhump scenario, and the phase-binned light curves presented in Figure 3 are similar to the superhumps observed in cataclysmic variables (CVs; Patterson et al. 2005) and X-ray binaries (O'Donoghue & Charles 1996; Zurita et al. 2002, 2008). Furthermore, the modulation is found to be color independent, as is also the case for superhumps (Zurita et al. 2008 and references therein). Persistent CVs show permanent superhumps with typical amplitudes (peak-to-peak) of ≈0.1 mag (Smak 2010). These are smaller than the ≈0.4 mag amplitude in 4U 1812–12 (Figure 3). However, superhumps with larger amplitudes (≈0.25−0.6) have been observed during CV superoutbursts (Smak 2010). These are also consistent with those found in superhumps detected during LMXB outbursts (≈0.1–0.6 mag; O'Donoghue & Charles 1996; Zurita et al. 2008; Thomas et al. 2022) and permanent superhumps in persistent LMXBs. For instance, a ≈0.6 mag amplitude permanent superhump has been detected in the ultracompact X-ray binary 4U 1915−05 (Callanan et al. 1995; Chou et al. 2001; Haswell et al. 2001; Retter et al. 2002), which has a low persistent luminosity, similar to 4U 1812–12.

It is important to bear in mind, however, that our observation spans two and a half periods, and therefore we cannot fully discard a noncoherent origin for the modulation, although we deem it unlikely. Rapid aperiodic variability with a suggested origin in the accretion disk is commonly observed in X-ray binaries (Shahbaz et al. 2003; Zurita et al. 2003; Hynes et al. 2004; Shahbaz et al. 2013; Casares & Jonker 2014). However, this flickering activity results in erratic variations of typically very short timescales (from seconds to minutes). Longer flares with timescales of hours have also been observed, particularly in systems with long orbital periods (e.g., the 6 hr flares in the 6.5 day orbital period LMXB V404 Cyg, Casares & Jonker 2014). However, such a long orbital period would require a much higher mass accretion rate in 4U 1812–12 to sustain its persistent nature, which would not be consistent with its observed X-ray luminosity. Flaring events produced by the compact jet are also unlikely, since the jet is not expected to make a dominant contribution to the optical emission in neutron star X-ray binaries (e.g., Russell et al. 2006; Migliari et al. 2010). Further, they should be more prominent in the red bands (e.g., Gandhi et al. 2016). All considered, although we cannot fully discard that the modulation may result from the detection of two ≈114 minute long, color-independent, and remarkably similar (in shape and amplitude) flares, a superhump origin for the observed modulation seems to be the most plausible scenario. We therefore tentatively propose an orbital period $P_{\rm orb}$ ≈114 minutes for 4U 1812–12.[10]

4. Discussion

4U 1812–12 is a strong ultracompact X-ray binary candidate. It shows several of the distinctive characteristics of the class, related to their compact geometry (small accretion disk) and nature (hydrogen-exhausted donor; see more details in in 't Zand et al. 2007; Armas Padilla & López-Navas 2019). In particular, since its discovery 50 yr ago by the Uhuru mission (Forman et al. 1976), the system has been repeatedly detected in the X-rays at ~(3–10) $\times 10^{-10}$ erg cm^{-2} s^{-1} (depending on the X-ray band), which together with the suggested distance of 2.3−4.6 kpc (Cocchi et al. 2000; Jonker & Nelemans 2004; Galloway et al. 2020), translates to a persistent X-ray luminosity of ~0.1–1 $\times 10^{36}$ erg s^{-1} (e.g., Warwick et al. 1981; Barret et al. 2003; Wilson et al. 2003; Muno et al. 2005; Tarana et al. 2006). This persistent activity at such low X-ray luminosity prompted in 't Zand et al. (2007) to propose an ultracompact orbit for the source, since only small disks can be entirely ionized at such low accretion rates (Lasota 2001). In the same way, Bassa et al. (2006) suggested a short orbital period based on the very dim optical counterpart ($g \simeq 25$, $r \simeq 23$ mag; Armas Padilla et al. 2020), since the X-ray (to optical) reprocessing scales with the size of the accretion disk (van Paradijs & McClintock 1994). Yet, possibly the most compelling evidence for the ultracompact nature of 4U 1812–12 is the absence of hydrogen features in its optical spectrum (Armas Padilla et al. 2020), in particular Hα, which is typically the most prominent optical emission line in LMXBs with hydrogen-rich donor stars (Charles & Coe 2006).

If we assume that 4U 1812–12 is indeed an ultracompact system (i.e., hydrogen-poor), the numerous short thermonuclear bursts displayed by the source would need to be fueled by pure He, pointing to a He-rich donor (see Armas Padilla et al. 2020). Considering evolutionary tracks for donor stars in ultracompact binaries, the derived mass transfer rate[11] of $\sim(3.4 \pm 2.5) \times 10^{-10}\, M_\odot$ yr^{-1} translates into an orbital period of ≃20 minutes and ≳35 minutes for a He white dwarf and a He-star donor, respectively. However, according to disk instability models for irradiated He accretion disks, the orbital period should be ≲25 minutes in order to sustain a stable disk (≲40 minutes in the case of a C/O disk; Menou et al. 2002; Lasota et al. 2008).

4.1. An Ultracompact X-Ray Binary Progenitor?

Our tentative $P_{\rm orb}$ ≈114 minutes lies outside the ultracompact zone of $P_{\rm orb} < 80$ minutes, contrary to what was expected from the aforementioned observational properties. The binary orbital separation is still large enough to fit a main-sequence star. In fact, a 114 minute orbit would require a very late M-type main-sequence star or a brown dwarf to fill its Roche lobe (Faulkner et al. 1972; Cox 2000; Rappaport et al. 2021). In such cases, the system mass ratio would be $q = M_2/M_1 < 0.04$ (assuming $M_1 = 1.4\, M_\odot$), which is in agreement with the low mass ratio required to produce superhump modulations (Whitehurst & King 1991). Further, according to evolutionary sequences for LMXBs, systems with an initial companion star mass ≈0.6−3 $M_\odot$ and an orbital period below the bifurcation period evolve by shrinking the orbit to a minimum period that can be as low as $P_{\rm orb} \simeq 80$ minutes (see, e.g., Rappaport et al. 1982; Podsiadlowski et al. 2002). Both scenarios could be valid for 4U 1812–12. However, the lack of hydrogen features in its optical spectrum is difficult to reconcile with these binary solutions. Nevertheless, we note that some transient LMXBs with hydrogen-rich companions did not show Hα emission during some phases of the outburst (see Jiménez-Ibarra et al. 2019; Stoop et al. 2021 and references therein).

A very appealing alternative for the nature of the system is that 4U 1812–12 is a progenitor of an ultracompact X-ray binary. In this case, the donor star would be an evolved main-sequence star that started mass transfer near or just after the point of central hydrogen exhaustion, and is progressively getting closer to the compact object on its path to the ultracompact period regime (i.e., the system is in the so-called evolved main-sequence star channel;

[10] Negative superhumps, with a period slightly shorter than the $P_{\rm orb}$, have also been detected in some systems, and are suggested to be produced by retrograde precession of a tilted disk.

[11] We derived the mass transfer rate following Coriat et al. (2012), assuming an average 2–10 keV X-ray unabsorbed continuum flux of 3.8×10^{-10} erg cm^{-2} s^{-1} (Cocchi et al. 2000), a bolometric correction of 2.9 (for which we account a 25% uncertainty; in 't Zand et al. 2007), and a distance of 2.3−4.6 kpc (Jonker & Nelemans 2004; Galloway et al. 2020).

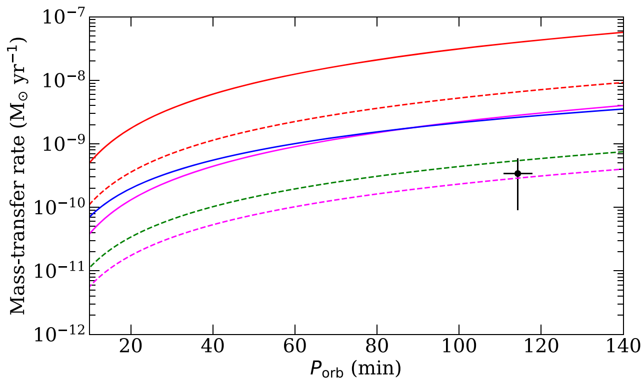

Figure 4. Stability limits for nonirradiated pure-helium disks (red solid line), for irradiated pure-helium disks (red dashed line), for nonirradiated C/O disks (blue solid line), for irradiated mixed-composition disks (green dashed line), for nonirradiated solar-composition disks (magenta solid line), and for irradiated solar-composition disks (magenta dashed line) according to Menou et al. (2002) and Lasota et al. (2008). The black dot corresponds to 4U 1812–12 assuming the tentative ≈114 minute orbital period and the mass transfer rate reported in this work (see Section 4).

see Nelemans et al. 2010). In this scenario, traces of hydrogen can still be present in the donor star photosphere ($X_s \sim 0.1$), and therefore in the accretion disk (Podsiadlowski et al. 2002; Nelson & Rappaport 2003; Nelemans et al. 2010). This scenario would reconcile all the observables of 4U 1812–12. First, this solution would be consistent with it being a persistent system, since the mass transfer rate is of the same order as the critical mass transfer rate in an accretion disk with mixed composition ($X = 0.1$ and $Y = 0.9$; Lasota et al. 2008; see Figure 4). Second, such a low fraction of hydrogen would not affect the duration of thermonuclear bursts (Cumming 2003), which is in agreement with the numerous short thermonuclear events displayed by the source (Cocchi et al. 2000; Galloway et al. 2020). Finally, this low fraction of hydrogen would not be detectable in the optical spectrum (Werner et al. 2006), in agreement with the observations of Armas Padilla et al. (2020).

4.2. An Ultracompact X-Ray Binary with a 114 minute Orbital Period?

According to evolutionary models, ultracompact X-ray binaries can evolve toward orbital periods of 100−110 minutes or longer if the donor is heated and inflated, or if the donor's mass loss via winds is taken into account (van Haaften et al. 2012a, 2012b). However, the predicted mass transfer rate at these longer periods is below $\sim 10^{-12}\ M_{\odot} \mathrm{yr}^{-1}$, which is two orders of magnitude lower than that of 4U 1812–12. We note that these computed tracks are for a helium or carbon–oxygen white dwarf companion that fully fills its Roche lobe. The evolutionary tracks for He-star donors presented in Heinke et al. (2013) provide higher mass transfer rates, which may explain the group of persistent ultracompact systems with orbital periods longer than ≃40 minutes and high mass accretion rates. Still, these tracks were calculated only for orbital periods up to 60 minutes. Thus, the evolution beyond this value is unclear, as is the stage where the He-star core stops expanding.

Setting aside the uncertainties that surround the above He-star evolutionary paths, this tantalizing scenario (i.e., an evolved 114 minute ultracompact system) might be still plausible from a pure stability point of view. Although the mass transfer rate of 4U 1812–12 sits below the disk instability lines for both pure-He and nonirradiated C/O disks, an irradiated C/O disk would maintain stability if the critical mass transfer rate drops by a similar amount than He and solar-abundance disks when irradiation is taken into account (i.e., by a factor of 6−10; see Figure 4; Menou et al. 2002; Lasota et al. 2008). As a matter of fact, evolutionary calculations show that He-star donors can be C/O-rich stars with some traces of helium left (Nelemans et al. 2010). Furthermore, we note that our calculated mass transfer rate is an upper limit, since it does not account for possible mass loss via outflows (see, e.g., Fender & Muñoz-Darias 2016; Marino et al. 2019; Hernández Santisteban et al. 2019), and therefore the actual mass transfer rate might still sit above the instability thresholds.

5. Conclusions

We have presented time-resolved HiPERCAM/GTC photometry of the ultracompact X-ray binary candidate 4U 1812–12. The $r_s i_s z_s$ light curves show a clear sawtooth-like periodic modulation that resembles a superhump. An ANOVA periodogram of the z_s-band light curve favors a period of ≃114 minutes. We tentatively propose this as the orbital period of 4U 1812–12, challenging the previously proposed ultracompact nature of the binary.

We discuss possible scenarios for the nature of the system. Based on its properties, namely its persistently dim luminosity, optical spectrum, and short thermonuclear type I bursts, we suggest that 4U 1812–12 is an ultracompact X-ray binary progenitor whose orbit is shrinking toward the ultracompact regime and has an evolved main-sequence star with a low fraction of photospheric hydrogen as donor star.

Additional high-quality observations of 4U 1812–12 are desirable in order to verify the persistence of the periodic modulation and confirm the orbital period of the system.

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Facilities: GTC(HiPERCAM).

Software: ANOVA (Schwarzenberg-Czerny 1996), HiPERCAM pipeline (https://github.com/HiPERCAM/), Peranso (www.peranso.com).

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