LETTER

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Swings between rotation and accretion power in a binary millisecond pulsar

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It is thought that neutron stars in low-mass binary systems can accrete matter and angular momentum from the companion star and be spun-up to millisecond rotational periods[1–3]. During the accretion stage, the system is called a low-mass X-ray binary, and bright X-ray emission is observed. When the rate of mass transfer decreases in the later evolutionary stages, these binaries host a radio millisecond pulsar[4,5] whose emission is powered by the neutron star's rotating magnetic field[6]. This evolutionary model is supported by the detection of millisecond X-ray pulsations from several accreting neutron stars[7,8] and also by the evidence for a past accretion disc in a rotation-powered millisecond pulsar[9]. It has been proposed that a rotation-powered pulsar may temporarily switch on[10–12] during periods of low mass inflow[13] in some such systems. Only indirect evidence for this transition has hitherto been observed[14–18]. Here we report observations of accretion-powered, millisecond X-ray pulsations from a neutron star previously seen as a rotation-powered radio pulsar. Within a few days after a month-long X-ray outburst, radio pulses were again detected. This not only shows the evolutionary link between accretion and rotation-powered millisecond pulsars, but also that some systems can swing between the two states on very short timescales.

The X-ray transient IGR J18245–2452 was first detected by INTEGRAL on 28 March 2013 and is located in the globular cluster M28 (see Supplementary Information). The X-ray luminosity of 3.5×10^{36} erg s^{-1} (0.5–10 keV), and the detection by the X-ray Telescope (XRT) on board Swift of a burst originated by a thermonuclear explosion at the surface of the compact object[19], firmly classified this source as an accreting neutron star with a low-mass companion. An observation performed by XMM-Newton on 4 April 2013 revealed a coherent modulation of its X-ray emission at a period of 3.93185 ms (Figs 1 and 2). We observed delays in the pulse arrival times produced by the orbit of the neutron star around a companion star of mass $>0.17 M_{\odot}$, with an orbital period of 11.0 h (see Fig. 2). The spin and orbital parameters of the source were further improved by making use of a second XMM-Newton observation, as well as two observations performed by Swift XRT (see Table 1).

Cross-referencing with the known rotation-powered radio pulsars in M28, we found that pulsar PSR J1824–2452I has ephemerides[20,21] identical to those of the INTEGRAL X-ray source IGR J18245–2452 (see Table 1). However, the X-ray pulsations we have observed from IGR J18245–2452 are not powered by the rotation of the magnetic field, unlike the radio emission of PSR J1824–2452I. The pulse amplitude

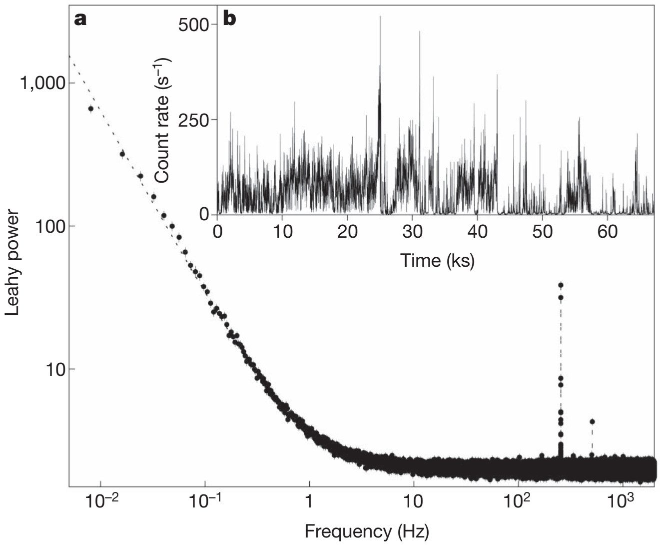

Figure 1 | Variability of the X-ray emission of IGR J18245–2452. a, Fourier power spectral density of the 0.5–10-keV X-ray photons observed by the EPIC pn camera on board XMM-Newton, during an observation starting on 13 April 2013, for an exposure of 67.2 ks (observation ID 0701981501). The power spectrum was obtained by sampling the light curve with a time binning of 0.236 ms, and averaging intervals 128 s in length. The times of arrival of photons were converted to the barycentre of the Solar System and to the line of nodes of the binary system hosting IGR J18245–2452, by using the parameters listed in Table 1. The peaks at 254.3 and 508.6 Hz represent the first and second harmonics of the coherent modulation of the X-ray emission of IGR J18245–2452. Considering photons observed during a 2-ks interval, not corrected for the pulsar orbital motion, the signal at the spin period of the neutron star is detected at a significance $\gtrsim 80\sigma$. The dashed solid line is the sum of a power-law noise function, $P(f) \propto f^{-\gamma}$, with $\gamma = 1.291(4)$, and of a white noise spectrum with an average value of 1.9900(2) Hz^{-1}. Even considering the whole length of the time series, no break in the power-law noise could be detected at low frequencies. **b**, Light curve in the 0.5–10 keV energy band of the same observation, with a bin time of 5 s. The possibility of contamination by soft proton flares was ruled out by extracting a light curve from a background region observed by EPIC-MOS cameras far from the source. Similar properties of variability to those shown here were observed during an XMM-Newton observation starting on 3 April 2013, for an exposure of 26.7 ks (observation ID 0701981401). Error bars show $\pm 1\sigma$.

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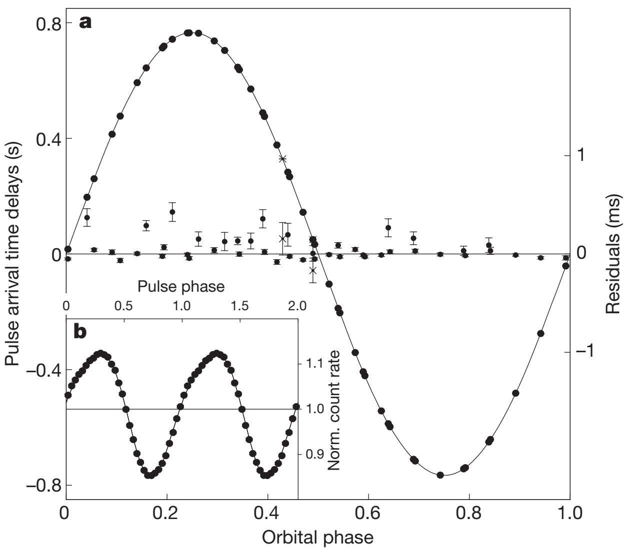

Figure 2 | Spin and orbit of IGR J18245–2452. a, Delays in pulse arrival time caused by the orbital motion of the neutron star (left axis) as measured by XMM-Newton during observations starting on 3 and 13 April 2013 (dots; observation IDs 0701981401 and 0701981501, with exposures of 26.7 and 67.2 ks, respectively), and by Swift during observations starting on 30 March and 7 April 2013 (crosses; observation IDs 00552369000 and 00032785005, with exposures of 0.6 and 1.6 ks, respectively). Residuals with respect to the best-fit timing solution (solid line) are also shown (right axis). Pulse profiles observed in intervals 2 ks long were modelled using $n = 12$ phase bins. The significance of each detection was assessed from the probability that the variance of each folded pulse profile was compatible with counting noise, assuming that in the absence of any signal the latter was distributed as a χ^2 variable with $(n - 1)$ degrees of freedom[29]. Only detections with a significance larger than 3σ were considered. Delays in pulse arrival time were determined through standard methods of least-square fitting of the pulse profiles[23], using two harmonic components and considering the values measured for the fundamental frequency component. **b**, Average pulse profile sampled in 32 phase bins, accumulated over the two XMM-Newton observations (black dots), and the best-fit decomposition with two harmonics (solid line). The amplitudes of the first and second harmonics were 13.4(1)% and 1.9(1)%, respectively. Two cycles are plotted for clarity. In both panels, plotted error bars are the standard deviation of each measure.

was observed to vary in strong correlation with the X-ray flux, implying that pulsations came from a source emitting $\sim 10^{36}$ erg s^{-1} in X-rays; this value is larger by more than two orders of magnitude than the luminosity shown by the X-ray counterparts of rotation-powered radio millisecond pulsars[22], whereas it agrees nicely with the X-ray output of accretion-powered millisecond pulsars[7]. The X-ray spectrum of IGR J18245–2452 was also typical of this class, and the broad emission line observed at an energy compatible with the Fe Kα transition (6.4–6.97 keV) is most easily interpreted in terms of reflection of hard X-rays by a truncated accretion disk[23] (see Supplementary Information and Supplementary Table 1). Furthermore, pulsations were detected by Swift XRT during the decay of a thermonuclear burst, after a runaway nuclear burning of light nuclei that had accreted on the neutron star surface (see Supplementary Information). Such bursts are unambiguous indicators that mass accretion is taking place[19], and the oscillations observed in some of them trace the spin period of the accreting neutron star[24].

We derived a precise position for IGR J18245–2452 by using a Chandra image taken on 29 April 2013, while the source was fading in X-rays. Analysis of archival Chandra observations from 2008 (see Supplementary Information and Supplementary Table 2) indicate that IGR J18245–2452 was already showing variations of its X-ray luminosity by an order of magnitude, as shown in Fig. 3, suggesting that it underwent other episodes of mass accretion in the past few years. This 2008 enhancement of the X-ray emission followed the nearest previous detection of the radio pulsar, on 13 June 2008, by less than two months, indicating a very rapid transition from rotation-powered to accretion-powered activity (see Supplementary Table 3 for a summary of past observations of the source in the X-ray and radio bands). The Chandra position of IGR J18245–2452 is compatible with a variable unpulsed radio source that we detected with the Australia Compact Telescope Array on 5 April 2013, with spectral properties typical of an accreting millisecond pulsar in outburst[25] (see Supplementary Information).

A combination of serendipitous and target-of-opportunity observations with the Green Bank Telescope (GBT), Parkes radio telescope and Westerbork Synthesis Radio Telescope (WSRT) partly map the reactivation of IGR J18245–2452 as the radio pulsar PSR J1824–2452I (see Supplementary Information and Supplementary Table 3). No pulsed radio emission was seen in any of the three observations in April 2013, compatible with the neutron star's being in an accretion phase and inactive as a radio pulsar. However, we caution that non-detection of radio pulsations from PSR J1824–2452I can also be due to eclipsing and that the lack of observable radio pulsations does not necessarily prove the absence of an active radio pulsar mechanism[20,22]. Radio pulsations were detected in 5 of the 13 observations conducted with GBT, Parkes and WSRT in May 2013. These observations show that the radio pulsar mechanism was active no more than a few weeks after the peak of the X-ray outburst.

In the past decade, IGR J18245–2452 has thus shown unambiguous tracers of both rotation-powered and accretion-powered activity, providing conclusive evidence for the evolutionary link between neutron stars in low-mass X-ray binaries and millisecond radio pulsars. The

Table 1 | Spin and orbital parameters of IGR J18245–2452 and PSR J1824–2452I

Parameter	IGR J18245–2452	PSR J1824–2452I
Right ascension (J2000)	18 h 24 min 32.53(4) s	
Declination (J2000)	–24° 52′ 08.6(6)″	
Reference epoch (MJD)	56386.0	
Spin period (ms)	3.931852642(2)	3.93185(1)
Spin period derivative	$<1.3 \times 10^{-17}$	
Root mean square of pulse time delays (ms)	0.1	
Orbital period (h)	11.025781(2)	11.0258(2)
Projected semimajor axis (light-seconds)	0.76591(1)	0.7658(1)
Epoch of zero mean anomaly (modified Julian date)	56395.216893(1)	
Eccentricity	$\leq 10^{-4}$	
Pulsar mass function ($M_\odot$)	$2.2831(1) \times 10^{-3}$	$2.282(1) \times 10^{-3}$
Minimum companion mass ($M_\odot$)	0.174(3)	0.17(1)
Median companion mass ($M_\odot$)	0.204(3)	0.20(1)

Coordinates, spin, and orbital parameters of IGR J18245–2452 = PSR J1824–2452I. Celestial coordinates of IGR J18245–2452 are derived from a Chandra X-ray observation performed using the High Resolution Camera (HRC-S) on 29 April 2013 (see Fig. 3). The spin and orbital parameters of IGR J18245–2452 were derived by modelling the delays in pulse arrival time of the fundamental frequency component, as observed in the 0.5–10-keV energy band by the EPIC pn camera on board XMM-Newton, and by the XRT on board Swift (see Fig. 2 and Supplementary Information for details). The solution covers the interval between 30 March and 13 April 2013. The peak-to-peak amplitude of the fundamental varied in correlation with the observed count rate (Spearman's rank correlation coefficient $\rho = 0.79$ for 45 points, which has a probability of less than 10^{-10} if the variables are uncorrelated), with a maximum of 18%. When detected, the second harmonic has an amplitude between 2% and 3%. The minimum and median masses of the companion star were evaluated for a $1.35 M_\odot$ mass of the neutron star, and for an inclination of the system of 90° and 60°, respectively. The spin and orbital parameters of PSR J1824–2452I were taken from ref. 20 and the Australia Telescope National Facility Pulsar Catalogue[21], considering errors on the last significant digit there quoted. The numbers in parentheses represent the uncertainties on the respective parameter evaluated at a 1σ confidence level. Upper limits are quoted at a 3σ confidence level.

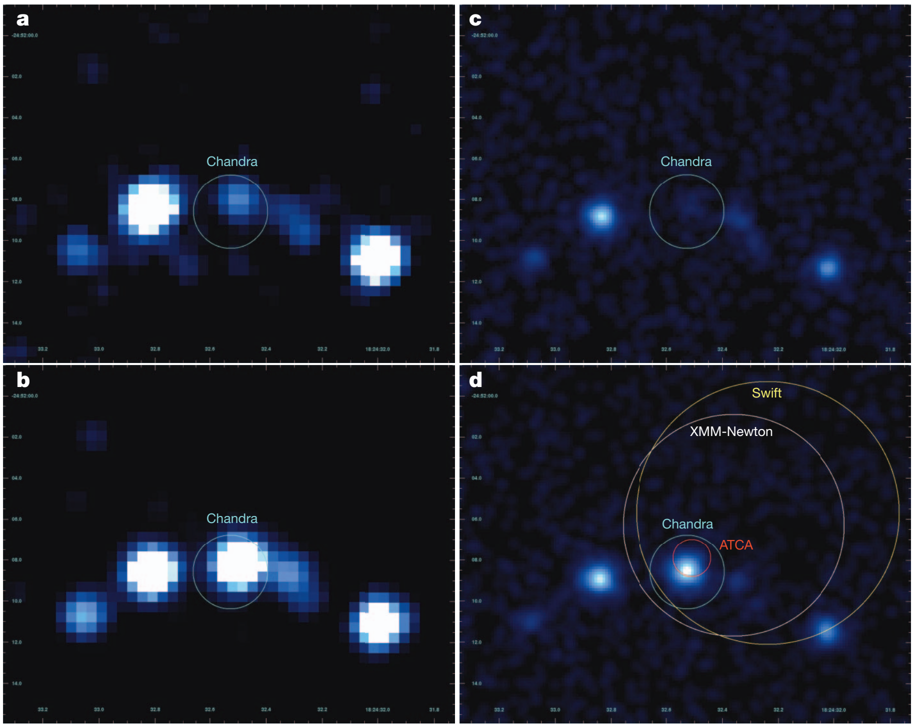

Figure 3 | Long-term X-ray variability of IGR J18245–2452. **a**, **b**, Chandra/ACIS-S images of the core of M28 taken during 4 August 2002 and 7 August 2008, respectively. **c**, **d**, Chandra/HRC-S images of the same field taken during 27 May 2006 and 29 April 2013, respectively. Images in **a** and **c** show the source in X-ray quiescence, emitting a luminosity of $\sim 1.5 \times 10^{32}$ erg s^{-1}, whereas during the observations shown in **b** and **d** the X-ray luminosity was of $\sim 2 \times 10^{33}$ erg s^{-1} (see Supplementary Information for details). The luminosity emitted during the 2013 observation (**d**) was three orders of magnitude lower than that observed by Swift (3.5×10^{36} erg s^{-1} on 30 March 2013) and XMM-Newton (1.1×10^{36} erg s^{-1} on 3 April 2013) at the onset of the X-ray outburst, compatible with the source being close to the end of the accretion episode. A distance[30] of 5.5 kpc was considered to derive these estimates. During the 2013 outburst, the 0.5–10-keV spectrum of IGR J18245–2452 was dominated by a power law with index ~ 1.4, interpreted as Comptonization in an optically thin medium, of seed photons with a temperature of ~ 0.3 keV. XMM-Newton observations also detected a thermal component, modelled as an accretion disc truncated at an apparent projected inner radius of ~ 50 km, and a broad line, modelled with a Gaussian centred at 6.74 ± 0.11 keV and of width 1.1 ± 0.2 keV, compatible with Fe Kα transition (see Supplementary Information for details). The plotted error circles represent the 3σ confidence level position of IGR J18245–2452, derived by Chandra (29 April 2013), XMM-Newton EPIC-MOS (3 and 13 April 2013), Swift XRT (30 March 2013) and ATCA (5 April 2013), plotted as cyan, white, yellow and red circles, respectively.

source swung between rotation-powered and accretion-powered states on timescales of a few days to a few months; this establishes the existence of an evolutionary phase during which a source can alternate between these two states over a timescale much shorter than the billion-year-long evolution of these binary systems, as they are spun-up by mass accretion to millisecond spin periods[26]. It is probable that a rotation-powered pulsar switches on also during the X-ray quiescent states of other accreting millisecond pulsars[14–18], even if radio pulsations have not yet been detected[27].

The short timescales observed for the transitions between accretion-powered and rotation-powered states of IGR J18245–2452 are comparable with those typical of X-ray luminosity variations. Like other X-ray transients, IGR J18245–2452 is X-ray bright ($L_X \approx 10^{36}$ erg s^{-1}) only during a few month-long periods called ‘outbursts’; outside these episodes it spends years in an X-ray quiescent state ($L_X \lesssim 10^{32}$ erg s^{-1}). These variations are caused by swings of the mass inflow rate onto the neutron star[13], and our findings strongly suggest that this quantity mainly regulates the transitions between accretion-powered and rotation-powered activity, which is compatible with earlier suggestions[5,10–12]. The X-ray luminosity of IGR J18245–2452 during quiescence ($L_X \approx 10^{32}$ erg s^{-1}) implies that the rate of mass accretion was not larger than $\dot{M} \lesssim 10^{-14} M_{\odot}$ yr^{-1} during such a state. The presence of millisecond radio pulsations indicates that the pulsar magnetosphere kept the plasma beyond the light cylinder radius (located at a distance of ~ 200 km), despite the pressure exerted by the mass inflowing from the companion star. A pulsar magnetic field of the order of 10^8–10^9 G is able to satisfy this condition and to explain the quiescent X-ray luminosity in terms of the pulsar rotational power (for a typical conversion efficiency of about 1%). The irregular disappearance of the radio pulses of PSR J1824–2452I during the rotation-powered stage suggests that, during that phase, most of the matter that the companion transfers towards the neutron star is ejected by the pressure of the pulsar wind[5,28]. A slight increase in the mass transfer rate may subsequently push the magnetosphere back inside the light cylinder[12]. After a disk had sufficient time to build up, an X-ray outburst is expected to take place, as in the case of IGR J18245–2452 during the observations reported here. As the mass accretion rate decreases during the decay of the X-ray outburst, the pressure of the magnetosphere is able to at least partly sweep away the residual matter from the surroundings of the neutron star, and a rotation-powered pulsed radio emission can reactivate. Our observations prove that such transitions can take place in both directions, on a timescale shorter than expected, perhaps only a few days.

The discovery of IGR J18245–2452, swinging between rotation-powered and accretion-powered emission, represents the most stringent probe of the recycling model[1–3], and the existence of an unstable intermediate phase in the evolution of low-mass X-ray binaries, offering an unprecedented opportunity to study in detail the transitions between these two states.

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Supplementary Information is available in the online version of the paper.

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Author Contributions A.Pa., C.F. and E.B. collected and analysed XMM-Newton data. A.Pa. and C.F. detected the pulsar in XMM-Newton data and derived its orbital solution. A.Pa. discovered the equivalence of its parameters with a radio pulsar, the thermonuclear burst and the burst oscillations. N.R. analysed Chandra data, detecting the X-ray quiescent counterpart of the source and past accretion events. L.P., M.H.W., M.D.F. and G.F.W. analysed ATCA data. E.B., S.C., P.R., A.Pa. and A.R. analysed Swift data. E.B. and C.F. analysed INTEGRAL data. J.W.T.H. analysed WSRT data. M.B. and J.M.S. analysed PKS data. J.W.T.H., S.M.R., A.Po., I.H.S. and P.C.C.F. analysed GBT data. A.R. provided software tools. A.Pa., N.R. and J.W.T.H. wrote the manuscript, with significant contribution by all the authors in interpreting the results and editing of the manuscript.

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