Unraveling the Nature of Transitional Millisecond Pulsars
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English summary

Neutron stars are exceptional probes of dense matter, strong gravity, and the interaction between an accretion flow and strong magnetic field.

Transitional millisecond pulsars (tMSPs) are binary systems in which there is a neutron star and a low-mass, likely non-degenerate companion star. These systems switch between states as: i) an observable radio millisecond pulsar (‘RMSP state’), at which time there is no evidence for an accretion disc, and ii) a state similar to that of a low-mass X-ray binary (LMXB), in which there is an accretion disc and sometimes apparently active accretion into the neutron star magnetosphere, or even a luminous X-ray outburst (‘LMXB state’).

In this thesis, ‘unravelling the nature of transitional millisecond pulsars’, we strive to understand the evolution and nature in the LMXB state of tMSPs; in particular, the persistent, low-luminosity, ‘disc-dominated’ state that they sometimes occupy.

As mentioned earlier in the Introduction, compared to other neutron-star-containing LMXBs this state is peculiar: it operates at a very low level of accretion and is highly stable — as demonstrated by the reproducible, two-mode X-ray lightcurve over the course of years. Studying this state holds the promise of answering: i) how and why switches between the RMSP and LMXB states happen, ii) at what point does a tMSP permanently transition to an RMSP (i.e. accretion ceases indefinitely), iii) how does the low-level accretion regime in LMXBs differ from the canonical quiescent/outbursting LMXB behaviour, and iv) can tMSPs teach us about the limiting factor in the maximum spin frequency a millisecond pulsar can achieve.

This thesis adds several new insights to our understanding of the best-studied tMSP, PSR J1023+0038, which has been intensively observed in both its RMSP and LMXB state (though it has yet to undergo a bright X-ray outburst like that seen in tMSP M28i). The close proximity of PSR J1023+0038 has allowed us to detect effects that may easily be masked in more distant tMSPs and LMXBs. To better understand how representative PSR J1023+0038 is of the tMSP class, we have also studied the candidate tMSP 3FGL J1544+1128. To try and connect tMSPs to the closely related class of accreting millisecond X-ray pulsars (AMXPs) we have also searched for radio pulsations from the prototype of this class, SAX J1808.4–3658, while it was in quiescence (not actively accreting).

In Chapter 2 we timed PSR J1023+0038 using XMM-Newton to track the coherent X-ray pulsations observed in its ‘high’ X-ray luminosity mode. Here our aim was to study the accretion versus ejection torques on the neutron star after it switched from RMSP to LMXB state in June 2013. We successfully modelled the spin-down behaviour of PSR J1023+0038 despite complications introduced by stochastic variations in its orbital parameters. We found that the spin-down rate in the LMXB state is comparable to what it was during the RMSP state, and hence that the pulsar mechanism (spin energy carried away by relativistic particle wind) is likely still active and dominates the torques on the neutron star, despite the lack of observable radio pulsations. This is first such continuous, long term timing solution for a persistently accreting neutron star. Furthermore, this timing solution (rotational ephemeris) has played a role in finding the first ever optical pulsations from an MSP (Ambrosino et al., 2017).

In Chapter 3 we performed an unprecedented multi-wavelength campaign on PSR J1023+0038 in the LMXB state using simultaneous observations with HST, XMM-Newton, NuSTAR, and Kepler. Here the primary idea was to compare simultaneous X-ray and optical/UV emission to identify the mechanisms that operate in the low-level accretion phase and cause minute-timescale high-/low-modes switches in tMSPs. This was motivated by the hypothesis that X-ray emission originates near the neutron star, whereas the optical/UV emission comes from further away in the disc. Finding connected variability, with or without relative time lags, would tell us about the underlying
physical mechanisms. Another aim was to search for coherent pulsations in the HST UV data. We discovered that UV emission shows the same moding behaviour as the X-rays and this points to both of them having a common emission mechanism. If we excise flares, correlation of the high and low mode from Kepler and XMM-Newton show zero lag. Although, we do observe that Kepler changes mode in an opposite direction to XMM-Newton. We therefore show that a single component in- deed connects the high-energy spectrum of the mode switching down to at least UV bands. However, the optical and radio mode changes happen in opposite direction to X-rays and UV. Our other aim here was to search for UV pulsations with HST, and we have found significant millisecond pulsations at the known rotation rate of the neutron star, a first such discovery for millisecond pulsars. Comparing with the previously known optical and X-ray pulsations suggests that they all come from the same process, which is plausibly a shocked accretion column in the neutron star magnetosphere. Though many questions still remain, these new observational facts bring us an important step closer to a self-consistent picture of what is changing in the system between the X-ray high mode (when we think that matter is entering the neutron star magnetosphere) and low mode (when we think that matter is being propeller-ed away by the neutron star’s magnetic field).

In Chapter 4 we study the candidate tMSP 3FGL J1544−1128. Besides PSR J1023+0038, it is currently the only (candidate) tMSP system in the LMXB state and therefore a very interesting avenue to understand if the radio continuum emission — representative of an outflow — is a universal property shared by tMSPs in the LMXB state. We discovered radio emission from 3FGL J1544−1128 and see that it populates the same region of the radio/X-ray luminosity (L−Lx) diagram as PSR J1023+0038. This finding suggests that it is in a similar accretion regime as PSR J1023+0038, and further solidifies 3FGL J1544−1128 as a very strong tMSP candidate. Continued monitoring is needed to catch any potential transition of this system to the RMSP state. Our findings in this chapter have also led to a new simultaneous radio/X-ray campaign in which we are trying to establish if 3FGL J1544−1128, like PSR J1023+0038, shows radio moding at the time of X-ray low/high modes (Gusinskaia, Jaodand et al., in prep). This will provide another important point of comparison to PSR J1023+0038, and hopefully a better understanding of the interplay between inflow and ejection in tMSPs.

Lastly, in Chapter 5, we studied an X-ray outburst from the well-known (and first to be discovered) AMXP, SAX J1808.4−3658. We studied the timing properties to ascertain whether orbital variation are truly secular (e.g. a widening orbit), or similar to the stochastic variations commonly seen in tMSPs and radio pulsars like the redbacks and black widows. Using the GBT, we also performed radio pulsation searches of SAX J1808.4−3658 when it was not accreting (i.e. in quiescence). The detection of radio pulsations would help solidify the link between the AMXPs and tMSPs by showing that during quiescence there is an active radio pulsar. Unfortunately, we have not found any significant radio pulsations but we provide the deepest pulsed radio emission constraint on SAX J1808.4−3658 to date. This upper limit points to a possible non-activation of AMXPs as radio millisecond pulsars during their quiescent LMXB state; however, we cannot rule out that there is an active radio pulsar that is simply too faint to detect, or not well beamed towards Earth.

In summary, we have undertaken wide-ranging, multi-wavelength explorations of tMSPs by searching, monitoring, timing and imaging them with individual and simultaneous observations spanning the electromagnetic spectrum through γ-ray, X-ray, UV and radio wavelengths. This has required a wide diversity of instruments and techniques, and these observations have led to significant insights into the nature of tMSPs, and in particular their persistent, low-level accretion state.