Probing Gravity and Accretion Using Neutron Stars
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English summary

The overarching theme of this thesis is the use of neutron stars to understand basic physical processes like accretion and the nature of gravity. We have done this primarily through joint radio and X-ray observations of low-mass X-ray binaries containing a neutron star. Astrophysical accretion occurs in a variety of contexts, and thus understanding the underlying processes can have broad application. In the case of accreting neutron stars, the deep gravitational well, ultra-strong magnetic field and rapid rotation are all ingredients that make them unique laboratories. The challenge is then to understand how these properties affect what we observe and, where possible, to compare and contrast with other astrophysical systems.

Combining (quasi-)simultaneous radio and X-ray measurements is a powerful way to probe accretion because it traces both the inflow of material (the inner accretion disk and potential matter transfer onto the neutron star) and the outflow (a collimated jet or other type of outflow). The work presented in the first part of this thesis (Chapters 2-4) explores such disk-jet connections in three neutron star low-mass X-ray binary systems, probing new or not-well-established phenomena over larger, previously unexplored luminosity ranges.

The final part of this thesis (Chapter 5) performs a fundamental test of gravitational theory using a radio millisecond pulsar that is in a hierarchical triple system with two white dwarf companions. This test exploits the precise, clock-like nature of millisecond pulsars, which are neutron stars that are thought to have acquired their rapid rotation via accretion like that studied in the earlier chapters of this thesis. In particular, we use this millisecond pulsar to test a very basic idea: that the gravitational acceleration experienced by bodies does not depend on their mass or composition. For example, if one were to drop a hammer and feather on the Moon (where there is no air resistance) then these should hit the surface at the same time. The pulsar experiment we performed is a much more extreme and precise test of the same basic idea, and the outcome is important for constraining the true nature of gravity.

In the following, we describe the motivations and findings of each chapter individually.

In Chapter 2, we explore the disk-jet connection in neutron star low-mass X-ray binary (NS-LMXB) 1RXS J180408.9−342850, presenting quasi-simultaneous radio (Very Large Array) and X-ray (Swift) observations of its first observed outburst. In total, six observations were performed: one in the hard X-ray state, one in the soft X-ray state and four during the decay phase of the outburst. Our main finding was that the radio jet became much dimmer (i.e. ‘quenched’) during the soft X-ray state, compared to the hard X-ray state. Such quenching has previously been observed in black hole (BH) LMXBs, but only in two out of five studied NS-LMXBs. The 1RXS J180408.9−342850 jet quenching we demonstrate in this chapter shows the largest brightness decrease (‘deepest’ quenching) and is the clearest example of the phenomenon in a NS-LMXB to date. It confirms that (transient) NS-LMXBs indeed show a similar jet—X-ray state connection as seen in BH-LMXBs. Since we had only one radio measurement in the hard X-ray state, our further exploration of any correlation between radio and X-ray luminosities was precluded. If 1RXS J180408.9−342850 again enters into an accretion-induced outburst, then high-cadence radio—X-ray monitoring should aim to better study the jet quenching during the soft X-ray state and to ascertain whether there is a clear coupling between radio and X-ray luminosity during the hard X-ray state.

1RXS J180408.9−342850 is a recently discovered source that we are only beginning to study. In contrast, in Chapter 3 we investigated the best-studied NS-LMXB Aql X-1 — using both new measurements we acquired in 2016, as well as a large collection of archival data reaching back to 2002 and sampling 7 previous outbursts. This system has the largest sample of radio—X-ray quasi-simultaneous measurements among all NS-LMXBs; still, we expanded the explored luminosity range by an order of magnitude with our new radio (Very Large Array) and X-ray (Swift) observations, which sampled the decay of the 2016 outburst. Although we did not detect the source, our non-detections placed strong upper limits on the energetics of any outflow and show that
Aql X-1 does not produce strong radio jets at low accretion levels. In order to place our new measurements in the context of previous observations, we completely revisited the archival measurements from 7 different outburst, carefully selecting only radio observations performed in the hard X-ray state (to prevent including quenched jet measurements related to the soft X-ray state, see Chapter 2) as well as including radio non-detections while performing the radio—X-ray power-law correlation fit. We found that Aql X-1’s radio—X-ray luminosities either follow a steeper (radiatively efficient) track, or can be modelled as a sharp radio cut-off at $L_X \approx 5 \times 10^{35}$ erg s$^{-1}$ if we compare with our newly obtained upper-limits. The overall picture sketched by analyzing the full sample of available radio—X-ray observations from all outbursts should be further tested by high-cadence sampling within a single outburst. Given that Aql X-1’s outbursts show a range of peak X-ray luminosity and spectral evolution, future observations can better determine what effect this has on the observed disc-jet coupling.

Both 1RXS J180408.9−342850 and Aql X-1 are relatively dim radio sources, and to make progress in our understanding we need to employ the most sensitive radio telescopes on Earth. In Chapter 4, we study a surprisingly bright NS-LMXB; we present the results of an extensive radio and X-ray monitoring campaign of the 2018 outburst of the newly discovered accreting millisecond X-ray pulsar IGR J17591−2342. Previously, NS-LMXBs were observed to have much weaker radio jets compared to BH-LMXBs at similar X-ray luminosities, by a factor of $\sim 20$. IGR J17591−2342, however, shows strikingly bright radio emission for a NS-LMXB, with a radio luminosity comparable to that of BH-LMXBs at the same X-ray luminosity. We found that the source was at its brightest in radio at the beginning of the outburst and its radio luminosity reduced significantly during the later stages of the outburst, with all these observations occurring at similar X-ray luminosities, overall showing a large scatter in the $L_R/L_X$ plane rather than a tight correlation. This highlights the importance of high-cadence sampling when studying the relation between disks and jets in accreting NS systems. Additionally, IGR J17591−2342 shares very similar spin, orbital and stellar companion properties with the three known transitional millisecond pulsars. To investigate whether the source would transition to a radio pulsar state, we performed Green Bank Telescope observations shortly after it returned to quiescence. We found no evidence for radio pulsations from IGR J17591−2342 in these observations, but we cannot rule out that IGR J17591−2342 becomes a radio millisecond pulsar during quiescence. The remarkable brightness of IGR J17591−2342 remains a mystery; NS-LMXBs show close to a factor of 100 spread in their radio luminosity within the X-ray luminosity range $4 \times 10^{35}$ erg s$^{-1} < L_X < 10^{37}$ erg s$^{-1}$ that is commonly observed during outburst. Yet, to date, there is no clear indication of how the physical parameters of the system — e.g. the magnetic field strength of the neutron star, or its spin rate — influence the radio brightness. Because IGR J17591−2342 is radio bright, it is potentially an excellent target for further observations in which radio and X-ray data are acquired strictly simultaneously. This will allow us to probe disk-jet coupling (and potentially other effects) on much shorter timescales, and may lead to new insights that have to date been missed by the available quasi-simultaneous measurements that are in-hand.

In the final Chapter 5, we present the results of an extensive timing analysis of a stellar triple system hosting a radio millisecond pulsar, PSR J0337+1715. We used this unique system to test the strong equivalence principle, which is a central tenet of Einstein’s theory of gravity, general relativity. This system permits a test that compares how the gravitational pull of the outer companion affects the pulsar, which has strong self-gravity (roughly 10% of its mass is in the form of gravitational binding energy), and the inner white dwarf (where self-gravity is comparatively negligible). We report that the accelerations of the pulsar and its nearby white dwarf companion differ fractionally by no more than $2.6 \times 10^{-6}$. In other words, gravitational binding energy is influenced in exactly the same way as normal matter, just as Einstein predicted. For a rough comparison, our limit on the strong-field Nordtvedt parameter $\tilde{\eta}_N$ is a factor of ten smaller than that obtained from (weak-field) Solar-System tests and a factor of almost a thousand smaller than that obtained from other strong-field tests. To achieve an accurate constraint, we needed to carefully model the influence of systematics in the pulsar timing data. This is the primary contribution of the PhD candidate to this work. We did this using a novel approach in which we estimated the unmodelled oscillations at various harmonics of the inner and outer orbital frequencies. Ultimately, the use of this system as a laboratory for testing gravity is limited by the systematics we quantified, as opposed to the raw precision of the pulsar timing measurements themselves. The origin of the systematics could possibly lie in unmodelled, time-variable propagation effects in the interstellar medium and solar system, which affect the pulse times of arrival in subtle ways. Future multi-frequency radio observations may be able to confirm this hypothesis.