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Radio emission from the X-ray pulsar Her X-1: a jet launched by a strong magnetic field neutron star?

J. van den Eijnden,[1★] N. Degenaar,[1] T. D. Russell,[1] J. C. A. Miller-Jones,[2] R. Wijnands,[1] J. M. Miller,[3] A. L. King[4] and M. P. Rupen[5]

[1]*Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands*
[2]*International Centre for Radio Astronomy Research – Curtin University, GPO Box U1987, Perth, WA 6845, Australia*
[3]*Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA*
[4]*KIPAC, Stanford University, 452 Lomita Mall, Stanford, CA 94305, USA*
[5]*Herzberg Astronomy and Astrophysics Research Centre, 717 White Lake Road, Penticton, BC, V2A 6J9, Canada*

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ABSTRACT

Her X-1 is an accreting neutron star (NS) in an intermediate-mass X-ray binary. Like low-mass X-ray binaries (LMXBs), it accretes via Roche lobe overflow, but similar to many high-mass X-ray binaries containing a NS; Her X-1 has a strong magnetic field and slow spin. Here, we present the discovery of radio emission from Her X-1 with the Very Large Array. During the radio observation, the central X-ray source was partially obscured by a warped disc. We measure a radio flux density of 38.7 ± 4.8 μJy at 9 GHz but cannot constrain the spectral shape. We discuss possible origins of the radio emission, and conclude that coherent emission, a stellar wind, shocks and a propeller outflow are all unlikely explanations. A jet, as seen in LMXBs, is consistent with the observed radio properties. We consider the implications of the presence of a jet in Her X-1 on jet formation mechanisms and on the launching of jets by NSs with strong magnetic fields.

Key words: accretion, accretion discs – stars: neutron – pulsars: individual: Her X-1 – X-rays: binaries.

1 INTRODUCTION

Her X-1 is an extensively-studied accreting X-ray pulsar, discovered with the *UHURU* satellite (Tananbaum et al. 1972). The pulsar has a low spin period of 1.24 s and is in a binary system with an orbital period of 1.7 d (Leahy & Abdallah 2014). Her X-1 was the first accreting neutron star (NS) where a cyclotron line was discovered (Trümper et al. 1978), with an energy of ∼40 keV. Although this energy varies with time and X-ray flux (e.g. Staubert et al. 2016), it provides a direct measurement of the pulsar magnetic field of a few times 10^{12} G.

Her X-1 shows peculiar variability in X-rays over a 35-d cycle, originating from the precession of a warped accretion disc (Scott & Leahy 1999, see also Fig. 1): the cycle starts in the bright Main High (MH) state, offering an unobscured view of the central X-ray source. This is followed with the Low State (LS), where the X-ray flux drops ∼99 per cent and only reflection off the face of the companion and an accretion disc corona are visible (Abdallah & Leahy 2015). This LS is interspersed by the Short High (SH) state, reaching a few tens of per cent of the original MH state flux. This variability is geometric, and the central X-ray source does not intrinsically vary on the 35-d time-scale.

The companion star of Her X-1 has a mass of 2.2 $M_{\odot}$ (Reynolds et al. 1997; Leahy & Abdallah 2014). At the simplest level, accreting NSs are classified based on the donor star mass into low-mass X-ray binaries (LMXBs, $\lesssim 1\,M_{\odot}$), high-mass X-ray binaries (HMXBs, $\gtrsim 10\,M_{\odot}$) and the rare intermediate-mass X-ray binaries (IMXBs) in between. Her X-1 is an IMXB but combines characteristics from both other classes: as in LMXBs, it accretes through Roche lobe overflow and an accretion disc (Scott & Leahy 1999), while most HMXBs accrete from the wind or circumstellar disc of the donor. In addition, Her X-1 has the strong magnetic field and low spin that are typically seen in HMXBs; NS LMXBs instead tend to have weaker magnetic fields of $B \lesssim 10^9$ G and if pulsations are seen, these are typically at millisecond periods (Patruno & Watts 2012).

Another observational difference between HMXBs and LMXBs is the presence of radio emission and inferred jets. LMXBs very commonly show synchrotron emission from jets, which is correlated with the X-ray emission from the accretion flow (Migliari & Fender 2006; Gusinskaia et al. 2017; Tudor et al. 2017), similar to accreting black holes (BHs; Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004). On the contrary, in NS HMXBs jets have only been observed in Cir X-1, a young NS that might have a high-mass donor (Johnston, Soria & Gibson 2016). As jet formation is still poorly understood, it is unclear which properties of NS LMXBs and HMXBs could explain this apparent systematic difference: the spin period, magnetic field, or the presence of

★ E-mail: a.j.vandeneijnden@uva.nl

an accretion disc might all play a vital role. As Her X-1 shares characteristics of both classes, it can help understand the difference between their jet launching abilities.

In this letter, we present the discovery of radio emission from Her X-1. We present the observations and results in Sections 2 and 3, and afterwards discuss the origin of the emission and implications for our understanding of jet formation in LMXBs and HMXBs. We also consider the possibilities for future observations.

2 OBSERVATIONS

2.1 Radio

We observed Her X-1 with the Karl G. Jansky Very Large Array (VLA) on 2013 June06 (MJD 56449) from 02:12:01 to 03:26:38 UT, for a total of ∼54 min of on-source observing time (project ID: 13A-352, PI: Degenaar). We observed the target in X-band between 8 and 10 GHz in two basebands, while the array was in C-configuration, yielding a synthesized beam of 3.24 arcsec × 1.8 arcsec (position angle 8.57°). We used J1331+305 and J1635+3808 (5.3° from the target) as the primary and secondary calibrators, respectively.

The observation was calibrated and imaged following standard procedures with the Common Astronomy Software Applications package (CASA) v4.7.2 (McMullin et al. 2007). We did not encounter any significant RFI or calibration issues. Using CASA's multifrequency, multiscale CLEAN task, we imaged Stokes I and V to make a source model of the field. With Briggs weighting and setting the robustness parameter to 0 to balance sensitivity and resolution, we reached an RMS noise of 4.8 μJy beam^{-1}. We fit a point source in the image plane by forcing the fit of an elliptical Gaussian with the FWHM and orientation of the synthesized beam. In addition, we also individually imaged the 8–9 and 9–10 GHz basebands with the same approach as the full band. As we did not observe a polarization calibrator, beam squint can affect our circular polarization estimates away from the pointing centre by a few per cent.

2.2 X-rays

We examined the X-ray properties of Her X-1 during the VLA epoch in order to obtain a simultaneous X-ray flux and determine the source's phase in the 35-d precession cycle. To measure the X-ray flux, we extracted the *MAXI*/Gas Slit Camera (GSC; Matsuoka et al. 2009) spectrum for the MJD of the VLA observation from the *MAXI* website (http://maxi.riken.jp). We extracted the spectrum for the full MJD to ensure a sufficient number of counts for a basic characterization of the spectrum. We also obtained the *MAXI*/GSC and *Swift*/Burst Alert Telescope (BAT) (Krimm et al. 2013) long-term X-ray light curves of Her X-1. Fig. 1 shows the *MAXI* and *Swift* light curves, clearly showing the 35-d cycle and revealing that Her X-1 was in the first LS of its precession cycle. Finally, we also downloaded the *MAXI* spectrum on MJD 56437, the peak of the prior MH state, to estimate the unobscured X-ray flux.

3 RESULTS

3.1 Radio

Her X-1 is detected at a flux density $S_\nu = 38.7 \pm 4.8$ μJy at 9 GHz, with a significance of 8σ. A zoom of the target field is shown in Fig. 2. For a distance of $d = 6.1$ kpc (e.g. Leahy & Abdallah 2014) and defining the radio luminosity $L_R = 4\pi \nu S_\nu d^2$, this corresponds to $L_R = (1.6 \pm 0.2) \times 10^{28}$ erg s^{-1}. The source is also detected in the 8–9 and 9–10 GHz bands separately at 42.2 ± 6.8 and 36.2 ± 6.8 μJy, respectively. However, the low significance means we do not well constrain the radio spectrum with $\alpha = -0.7 \pm 5.3$, where $S_\nu \propto \nu^\alpha$.

We measured a position of RA = $16^h57^m49^s.792 \pm 0^s.027$ and Dec. = $+35°20'32''.578 \pm 0''.225$, where the uncertainties equal the synthesized beam size divided by the signal-to-noise of the

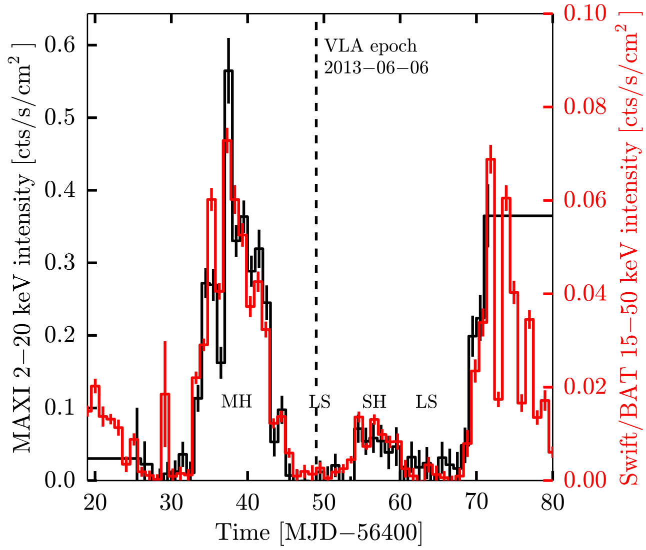

Figure 1. *MAXI* /GSC and *Swift*/BAT daily X-ray light curves of Her X-1 around the radio epoch on MJD 56449. The 35-d cyclic variability, due to precession of the warped accretion disc, is clearly visible. The VLA epoch is shown by the dashed line.

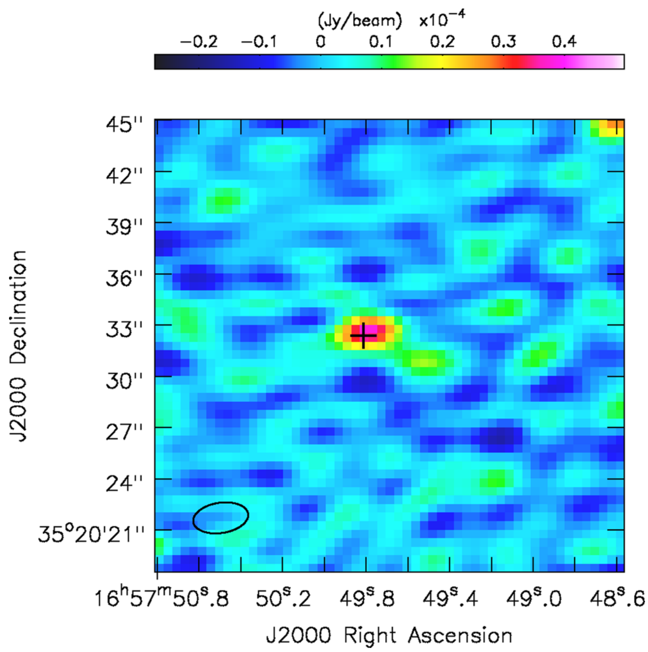

Figure 2. VLA image of Her X-1 at 9 GHz. The black cross indicates the best known position, from the infrared 2MASS survey. In the bottom left corner, we show the half-power contour of the synthesized beam.

detection. This position is consistent within the 1σ errors with the best known position of Her X-1, from the infrared 2MASS survey (Skrutskie et al. 2006), which is shown in Fig. 2 as well, and with the lower accuracy positions at other wavelengths. Hence, this is unlikely to be a background source.

3.2 X-rays

We fit the two downloaded *MAXI* 2–20 keV spectra of Her X-1 to determine the flux on the MJD of the radio observation and at the height of the previous MH state. As the latter is only a short (∼120 s) exposure, both spectra contain few photons (∼145 and 40 photons, respectively) and are only suitable for a very simple fit. In both cases, we used XSPEC to fit an absorbed (TBABS) blackbody (BBODYRAD) spectrum. We fix the $N_{\rm H}$ in both cases, as the data quality is not sufficient to determine it directly. We set $N_{\rm H} = 1.0 \times 10^{22}$ for the obscured LS (İnam & Baykal 2005) and $N_{\rm H} = 1.7 \times 10^{20}$ cm^{-2} in the HS (Fürst et al. 2013). This yields 0.5–10 keV X-ray fluxes of $\sim 9 \times 10^{-11}$ erg s^{-1} cm^{-2} during the radio observation and $\sim 3 \times 10^{-9}$ erg s^{-1} cm^{-2} during the MH state. The latter is slightly lower than the typical range of X-ray fluxes of Her X-1 in the MH state of 5×10^{-9} to 10^{-8} erg s^{-1} cm^{-2} (Staubert et al. 2016). This difference might be due to the short exposure of the *MAXI* spectrum, combined with the dips often seen during the MH state (Igna & Leahy 2011).

4 DISCUSSION

We present the first radio detection of the IMXB Her X-1, at a flux density of $S_\nu = 38.7 \pm 4.8$ μJy. Her X-1 has been the subject of multiple radio searches, but similar to most NS HMXBs, was hitherto never detected. Coe & Crane (1980) observed Her X-1 every day of an entire 35-d precession cycle. The source was not detected in any of the observations, with 3σ upper limits of 9 mJy. Nelson & Spencer (1988) observed Her X-1 twice in a large sample study of X-ray binaries and cataclysmic variables, reaching a 5σ upper limit of 1.3 mJy. In this discussion, we will first compare the radio properties of Her X-1 with different classes of accreting NSs. Subsequently, we will discuss the origin of the radio emission and implication for future research.

4.1 Comparison with NS LMXBs and HMXBs

Radio detections and jets are ubiquitous in disc-accreting, weak magnetic field NS LMXBs (Migliari & Fender 2006; Gusinskaia et al. 2017; Tudor et al. 2017). While L_X and L_R do appear to be related for these types of NS systems, no universal relation has emerged (Tudor et al. 2017). Most relevant for the comparison with Her X-1 are the handful of LMXBs containing a slow pulsar. With the exception of one (see below), none of these sources have been detected in the radio. 2A 1822-371 and 4U 1626-67 have unconstraining upper limits on their radio flux of 200 μJy (Fender & Hendry 2000). GRO 1744-28 (The Bursting Pulsar) does have deep *ATCA* upper limits during it small 2017 outburst (Russell et al. 2017). Finally, for the mildly recycled 11-Hz pulsar IGR J1748-2466 no radio upper limits are known.

As stated, a single slow pulsar in an LMXB has been detected: the symbiotic X-ray binary GX 1+4 was recently discovered in radio (van den Eijnden et al. 2017). In this type of source, the NS accretes from the stellar wind of an evolved low-mass companion. The origin of the radio emission in GX 1+4 cannot be unambiguously inferred. Other symbiotic X-ray binaries have not been targeted by radio campaigns and it is thus unknown whether radio emission occurs in more sources of this type. Given the current upper limits or lack of observations, new, deep radio observations are needed to infer whether Her X-1 is an outlier among slow pulsars in LMXBs or whether radio emission occurs more commonly among such sources.

Her X-1 also shares characteristics with many of the NS HMXBs: a strong magnetic field ($\gtrsim 10^{12}$ G) and a slow spin. Radio detections of HMXBs are relatively rare (Duldig et al. 1979; Nelson & Spencer 1988; Fender & Hendry 2000; Migliari, Miller-Jones & Russell 2011): the NS Cir X-1 launches resolved radio jets (Tudose et al. 2006), and likely is an HMXB (see Johnston et al. 2016, for a recent discussion). However, no magnetic field estimate is known for Cir X-1. Two other NS HMXBs have been detected in radio. Most notably, the wind-accreting HMXB GX 301-2 was detected over multiple radio epochs (Pestalozzi et al. 2009). However, the flux levels were consistent with those expected from the stellar wind, and the claimed transient outflow component in the emission has not been confirmed (Migliari et al. 2011). Additionally, the Be/X-ray binary A 1118-61, consisting of a NS and a Be companion, was detected in only one out of eight observations by Duldig et al. (1979). Due to the crowded field, this detection might not be related to the Be/X-ray binary. Both these (possible) detections are thus not conclusive about the presence of a jet.

There exist numerous radio non-detections of NS HMXBs. However, for most of these sources, the radio upper limits (ranging from hundreds of μJy to mJy levels; Duldig et al. 1979; Nelson & Spencer 1988; Fender & Hendry 2000) are not constraining compared with NS LMXBs and deep observations with current generation radio telescopes might reveal these sources. Only the Be/X-ray binaries A 0535+26 (Tudose et al. 2010) and X Per, and the wind-accreting NS HMXB 4U 2206+54 (Migliari & Fender 2006) have radio luminosity upper limits of $\lesssim 5 \times 10^{27}$ erg s^{-1}, below our Her X-1 measurement. However, these sources were observed at much lower (more than an order of magnitude) X-ray luminosity, making any direct comparison with Her X-1 difficult.

4.2 The emission mechanism and physical origin

Three radio emission mechanisms are relatively unlikely to explain our detection of Her X-1. First, thermal emission would require too high densities of emitting material on too large scales. Secondly, we imaged Stokes V in addition to Stokes I and did not detect the target, setting a 3σ upper limit on the circular polarization of 37 per cent. Coherent emission should be highly circularly polarized and can thus be excluded. Finally, free–free emission from a strong stellar wind, as observed in the HMXB GX 301-2 (Pestalozzi et al. 2009), is unlikely: while a wind might be present (Leahy 2015), its strength implies a flux density over two orders of magnitude lower than our detection (Wright & Barlow 1975). On the contrary, synchrotron emission is consistent with the observed radio properties. In the following, we will discuss possible physical origins of such synchrotron emission.

First, synchrotron-emitting shocks could occur in the interaction between the disc and the magnetosphere or in the accretion column on to the magnetic poles. However, the Compton limit on the brightness temperature of 10^{12} K sets a lower limit on the size of the emitting region of $\gtrsim 7.5 \times 10^4$ km. We can estimate the size of the magnetosphere R_m by rewriting equation (1) from Cackett et al. (2009):

$$R_m = k\left(\frac{B}{1.2\times10^5\,\mathrm{G}}\right)^{4/7}\left(\frac{f_{ang}}{\eta}\frac{F_{bol}}{10^{-9}\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{-4/14}\left(\frac{M}{1.4\,\mathrm{M_\odot}}\right)^{-8/7}\left(\frac{R}{10\,\mathrm{km}}\right)^{-12/7}\left(\frac{D}{5\,\mathrm{kpc}}\right)^{-4/7}R_g \quad (1)$$

where k is a geometry factor relating spherical and disc accretion, typically assumed to be 0.5 for disc accretion, B is the magnetic field strength, f_{ang} is the anisotropy correction factor, η is the accretion efficiency, F_{bol} is the bolometric flux, and M, R and D are the mass, radius and distance of the NS. We use $B\sim3\times10^{12}$ G (Staubert et al. 2016), $k=0.5$, $f_{ang}=1$, $\eta=0.1$, $M=1.4\,\mathrm{M_\odot}$, $R=10$ km (Leahy 2004) and D = 6.1 kpc (Leahy & Abdallah 2014).

As R_m scales inversely with flux, the maximum magnetospheric size can be estimated with the LS 2–10 keV X-ray flux without a bolometric correction (e.g. 9×10^{-11} erg s^{-1} cm^{-2}): this yields $R_m\approx1.7\times10^4$ km, smaller than the minimum emission region size. As the low flux during the LS of Her X-1 originates from a geometric effect, it is actually more accurate to use the MH state bolometric flux; for the measured MH state flux of 3×10^{-9} erg s^{-1} cm^{-2}, R_m is even smaller at $\sim0.7\times10^4$ km. Hence, shocks can be excluded as well, assuming that they indeed occur at the magnetosphere and not further out in the accretion flow.

Another possibility is that we observe a propeller-driven outflow: if the magnetosphere spins faster than the disc where the magnetic and gas pressure are equal, it creates a centrifugal barrier that can either trap the disc (D'Angelo & Spruit 2010) or expel the material (Illarionov & Sunyaev 1975; Campana et al. 1998). The latter has, for instance, recently been inferred through X-ray monitoring in several strong magnetic field accreting NSs (e.g. two Be/X-ray binaries; Tsygankov et al. 2016) and might explain the recent radio detection of GX 1+4 (van den Eijnden et al. 2017). For a given NS magnetic field and spin period, one can estimate the maximum L_X for which the magnetosphere can still create this centrifugal barrier as (e.g. Campana et al. 2002):

$$L_{X,max}\approx4\times10^{37}k^{7/2}\left(\frac{B}{10^{12}\mathrm{G}}\right)^2\left(\frac{P}{1\,\mathrm{s}}\right)^{-7/3}\left(\frac{M}{1.4\,\mathrm{M_\odot}}\right)^{-2/3}\left(\frac{R}{10\,\mathrm{km}}\right)^5\mathrm{erg\,s^{-1}} \quad (2)$$

where P is the pulsar spin and all other parameters are already defined. For a magnetic field of $\sim3\times10^{12}$ G, a spin period of 1.24 s and standard NS parameters, we estimate the $L_{X,max}\approx1.9\times10^{37}$ erg s^{-1} for Her X-1.

To assess whether a magnetic propeller could be at play in Her X-1, we need to compare this maximum X-ray luminosity with the correct L_X of Her X-1. During the LS radio epoch, $L_X\approx4\times10^{35}$ erg s^{-1}, comfortably below the upper limit for the propeller effect. However, the actual, unobscured X-ray luminosity is the more accurate probe of the relevant physical properties (i.e. the mass accretion rate that balances the magnetic pressure). During the prior MH state, Her X-1 reached $L_X\approx1.2\times10^{37}$ erg s^{-1} between 2–10 keV. With a bolometric correction, the X-ray luminosity of Her X-1's MH state typically reaches (2.5–5) $\times10^{37}$ erg s^{-1} (Staubert et al. 2016). This is of comparable magnitude as the $L_{X,max}$ estimate, although it should be noted that not every MH state reaches the same luminosity (e.g. Staubert et al. 2016) and equation (2) is merely an estimate. However, in other accreting NSs propellers have been linked to a simultaneous decrease in X-ray flux and pulsation strength and such behaviour has not been observed in Her X-1 in its regular, 35-d cyclic behaviour.

Finally, we might observe a compact, synchrotron-emitting radio jet, similar to those seen in NS LMXBs with weaker ($\lesssim10^9$ G) magnetic fields. If we compare Her X-1's radio properties with the NS LMXB sample in the L_X/L_R diagram (see e.g. Gusinskaia et al. 2017; Tudor et al. 2017, for recent versions), we see that these are consistent with several accreting millisecond X-ray pulsar (AMXP) observations if we assume the LS flux. While an interesting comparison, as AMXPs have ∼3–4 orders of magnitude weaker magnetic fields and faster spins, we should actually again use the estimated unobscured (i.e. MH state) flux. In that comparison, the L_R of Her X-1 is three to ten times lower than hard-state and several soft-state Atoll sources at similar L_X, and more similar to that of jet-quenched sources (e.g. Gusinskaia et al. 2017).

As jet formation is poorly understood, the cause of jet quenching is puzzling. It is observed in all BH LMXBs if and when they transition into the soft spectral state (e.g. Gallo, Fender & Pooley 2003), but the picture is more ambiguous in accreting NSs: only in a handful of sources is quenching observed (see e.g. Miller-Jones et al. 2010; Gusinskaia et al. 2017). If jet formation requires large scale-height poloidal magnetic fields, quenching might be explained as follows: in the hard spectral state, the accretion disc might be truncated away from the compact object (e.g. Done, Gierlinski & Kubota 2007) as a radiatively inefficient accretion flow (RIAF; Narayan & Yi 1995) or corona replaces the inner disc, providing the required fields. As the disc moves inwards during the transition to softer spectral states, the RIAF disappears or the corona is cooled, breaking the jet formation mechanism.

If the above scenario indeed underlies jet quenching, it is difficult to reconcile with the low L_R in Her X-1: there, the strong stellar magnetic field prevents the disc from moving inwards. However, this stellar field might instead hamper the initial formation of a RIAF or corona, also effectively quenching the jet. Alternatively, the jet formation might be partially suppressed as the disc pressure cannot dominate and twist the strong magnetic field (Massi & Kaufman Bernadó 2008), or as the magnetic field prevents the formation of a boundary layer at the NS surface, which might play a role in NS jet formation (Livio 1999).

4.3 Implications for future research

Out of the considered origins for the radio emission (shocks, a propeller outflow and a compact jet), a jet appears most compatible with both the correlated X-ray and radio properties and with the known properties of the Her X-1 system. The presence of a jet in Her X-1 automatically implies that (the combination of) a strong magnetic field and a slow spin do not completely impede jet formation (as suggested by, e.g. Massi & Kaufman Bernadó 2008). This would imply that our understanding of jet formation, in the presence of a strong NS magnetic field, needs to be revisited. Additionally, it opens up the possibility of observing radio emission from several currently undetected sources: for instance, the LMXBs containing slow X-ray pulsars and Be/X-ray binaries accreting from a (small) disc would be prime targets for such studies, as current generation radio telescopes (e.g. *VLA*, *ATCA*) reach sensitivities orders of magnitude below the current typical upper limits for these sources.

In order to confidently confirm a jet nature of the radio emission in Her X-1, new observations are necessary. A measurement of the radio spectral index, combined with a linear polarization measurement, and a search for extended structure or a jet-break in the spectrum, could reveal the emission mechanism. If a jet is indeed present, this opens up interesting possibilities to better understand Her X-1 itself. For instance, observations at different states during its 35-d cycle could independently confirm that precession causes this cycle, as the jet likely emits from further out without being obscured. Additionally, a jet might be a better tracer of the mass accretion rate on to the NS than the X-rays, if it is indeed not influenced by obscuration. That could possibly also allow a more detailed study of Her X-1's rare off state, wherein barely any X-ray emission is observed for extended periods of time.

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