Superhumps in Low–Mass X–Ray Binaries

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ABSTRACT

We propose a mechanism for the superhump modulations observed in optical photometry of at least two black hole X-ray transients (SXTs). As in extreme mass–ratio cataclysmic variables (CVs), superhumps are assumed to result from the presence of the 3:1 orbital resonance in the accretion disc. This causes the disc to become non–axisymmetric and precess. However the mechanism for superhump luminosity variations in low mass X-ray binaries (LMXBs) must differ from that in CVs, where it is attributed to a tidally–driven modulation of the disc’s viscous dissipation, varying on the beat between the orbital and disc precession period. By contrast in LMXBs, tidal dissipation in the outer accretion disc is negligible: the optical emission is overwhelming dominated by reprocessing of intercepted central X-rays. Thus a different origin for the superhump modulation is required. Recent observations and numerical simulations indicate that in an extreme mass–ratio system the disc area changes on the superhump period. We deduce that the superhumps observed in SXTs arise from a modulation of the reprocessed flux by the changing area. Therefore, unlike the situation in CVs, where the superhump amplitude is inclination–independent, superhumps should be best seen in low–inclination LMXBs, whereas an orbital modulation from the heated face of the secondary star should be more prominent at high inclinations. Modulation at the disc precession period (10s of days) may indicate disc asymmetries such as warping. We comment on the orbital period determinations of LMXBs, and the possibility and significance of possible permanent superhump LMXBs.

Key words: accretion, accretion discs – stars: binaries close – stars: individual: 4U 1915-05, GX 9+9, GS 1124-68, GRO J0422+32, GS 2000+25, GRS 1716-249

1 INTRODUCTION

Superhumps are periodic optical modulations observed in superoutbursts of the SU UMa dwarf novae (see Warner, 1995 for a review). Their most striking property is that their periods \( P_{sh} \) are slightly longer than the orbital period \( P_{orb} \), typically by 1 – 7 %. Since the work of Whitehurst (1988), Whitehurst & King (1991) and Lubow (1991a, b) it is now understood that superhumps are a consequence of the presence of the 3:1 orbital resonance within the accretion disc. This causes the disc to become eccentric, and to undergo slow prograde precession in the inertial frame. The secondary star thus repeats its motion with respect to the disc on the beat period between the orbit and this precession, which is therefore slightly longer than \( P_{orb} \). This relative motion of the secondary star modulates the disc’s streamline geometry on the superhump period, causing its viscous dissipation to vary on the same period. This intrinsic variation of the disc light satisfies one of the basic observational features of CV superhumps, namely that their occurrence is independent of binary inclination (Warner 1995, section 3.6.4.1).

The defining resonance condition restricts the mass ratio \( q = M_2/M_1 \) to extreme values

\[
q \lesssim 0.33.
\]

Since in most CVs the white dwarf mass \( M_1 \) lies in a narrow range (\( \sim 0.6 – 0.8M_\odot \)), and \( M_2 \) is often strongly correlated with the orbital period \( P = P_{orb} \) hr (i.e. \( M_2/M_\odot \approx 0.11P_{hr} \)), this confines the occurrence of superhumps to short orbital periods, mostly below the CV period gap (so \( P_{sh} \ll 2 \)). In practice almost all of these systems are dwarf novae, with the superhumps occurring during superoutbursts. However persistent systems satisfying the resonance condition \( q \) do exist, and show the superhump phenomenon permanently (‘permanent superhumpers’, Patterson 1999). ‘Negative superhumps’, in which \( P_{sh} < P_{orb} \), also exist, and clearly correspond to retrograde disc precession in the inertial frame.
There is no currently accepted explanation for the retrograde precession inferred from negative superhumps in CVs. Murray (2000) shows that the precession period, and thus the quantity

$$
\epsilon = \frac{P_{sh} - P_{orb}}{P_{orb}},
$$

depend on both the mass ratio and other conditions such as the disc pressure or temperature. Small mass ratios \(q\) produce small \(\epsilon\), as does a high disc temperature. Taking this to extremes, an extreme mass ratio system with a very hot disc could have a disc with retrograde precession.

## 2 SUPERHUMPS IN LMXBS

The resonance condition (1) is easily fulfilled in binaries with large primary masses \(M_1\). The prevalence of superhumps in outbursting CVs suggests that soft X-ray transients, particularly those containing black holes, (see Marsh 1998 for a review) might be prime candidates for showing superhumps. Recognising this, O’Donoghue and Charles (1996) carefully surveyed the available observational evidence, and concluded that superhumps had been seen in outbursts of at least two black-hole SXs (GS1124-68 = X-Ray Nova Mus 1991, GRO J0422+32, and probably GS 2000+25). At about the same time, superhumps were claimed in observations from the 1993 outburst of GR2 1716-240 (=X-Ray Nova Oph 1993 = GRO J1719-24, Masetti et al 1996), but as the orbital period of this system is unknown, this claim cannot be rigorously assessed. It is notable that the superhump excesses \(P\) are only \(\sim 1-2\%\), which with \(P_{orb} \gtrsim 5\)hr, implies much longer disc precession periods, \(P_{precc} = P_{sh}/\epsilon \sim 10-50\) days, than in CVs.

Although supporting the importance of the 3:1 orbital resonance, the existence of superhumps in LMXBs comes as an unexpected difficulty. The intrinsic dissipation in LMXB discs has long been known to be a negligible contributor to their optical light (e.g. van Paradijs and McClintock 1995). The argument is simple. The X-ray luminosity \(L_X\) gives an estimate of the accretion luminosity \(\dot{M}c^2\) (where \(\eta \sim 10^{-6}\) erg g \(^{-1}\) is the efficiency of rest-mass conversion) and thus the accretion rate \(\dot{M}\) on to the central star (neutron star or black hole) in an LMXB. This immediately gives an estimate of the optical luminosity \(L_{opt}(\text{visc})\) of a steady-state accretion disc surrounding the central object (cf Frank et al., 1992). For all persistent LMXBs the ratio \(L_{opt}(\text{visc})/L_X\) predicted by this method is far smaller than the observed value (van Paradijs & McClintock 1995). This conclusion can be extended to SXTs in outburst, as their period of this system is unknown, this claim cannot be rigorously assessed. It is notable that the superhump excesses \(P\) are only \(\sim 1-2\%\), which with \(P_{orb} \gtrsim 5\)hr, implies much longer disc precession periods, \(P_{precc} = P_{sh}/\epsilon \sim 10-50\) days, than in CVs.

The explanation for the excess optical luminosity of LMXBs is straightforward. If the disc intercepts even a small fraction of the central X-ray luminosity, this completely dominates its own intrinsic dissipation. For a point source at the centre of the disc, the irradiation temperature \(T_{irr}\) is given by

$$
T_{irr}^4 = \frac{\eta \dot{M}c^2(1 - \beta) H}{4\pi \sigma R^2} \frac{H}{g}.
$$

(e.g. van Paradijs, 1996) Here \(\beta\) is the X-ray albedo, \(H(R)\) is the local disc scaleheight, and

$$
g = \left(\frac{d \ln H}{d \ln R} - 1\right).
$$

Viscous dissipation alone gives an effective temperature \(T_{visc}\) with (e.g. Frank et al. 1992)

$$
T_{visc}^4 = \frac{3GM\dot{M}}{8\pi \sigma R^2}
$$

at disc radii \(R\) much larger than the radius, \(r_s\), of the central object (mass \(M\)). Dividing, one finds

$$
\frac{T_{irr}^4}{T_{visc}^4} = \frac{2\eta c^2}{3GM} \left(\frac{H}{R}\right) \frac{gR}{(1 - \beta)}
$$

For LMXBs, the combination \((2\eta c^2/3GM)(1 - \beta)\) is of order \(r_s^{-1}\), where \(r_s\) is the radius (e.g. event horizon) of the central star. Thus for a large enough disc, i.e. one with \(R >> r_s(R/H_g)\), irradiation wins over intrinsic dissipation despite the small solid angle \(\sim H/R\) of the disc, because \(T_{irr}\) falls off only as \(R^{-\frac{1}{2}}\), whereas \(T_{visc}\) goes as \(R^{-\frac{3}{2}}\). This condition is very easily satisfied in all LMXBs \((R/r_s \lesssim 10^4\), while \(R/H_g \lesssim 10^3\)). \(L_{opt}\) is thus predominantly a result of disc irradiation. In agreement with this, van Paradijs & McClintock (1994) show that for a sample of 18 LMXBs the observed \(L_{opt}\) scales with \(L_X\) and disc size approximately as expected.

It is perhaps worth noting that the mere existence of efficiently irradiated discs is a challenge to theory, which usually predicts that a disc heated by central X-rays adopts a convex shape (formally \(g < 0\)), and thus shields most of its area from the central flux (e.g. Cannizzo 1994, Dubus et al 1999). However the observational evidence that LMXB discs are irradiated is overwhelming, and we adopt this view here (cf King & Ritter, 1998).

The overwhelming dominance of irradiation over intrinsic dissipation means that the explanation of the superhump luminosity variations in CVs will not work for LMXBs. The intrinsic dissipation at a given disc radius \(R\), e.g. the resonant radius, varies as the local accretion luminosity \(L_{acc}(R) = GM/R\) the compactness \(M/r_s\) of the central object is irrelevant. The intrinsic superhump luminosities \(L_{sh}\) in LMXBs and CVs are thus in the ratio \((M/R)_{LMXB}/(M/R)_{CV}\). Even for black-hole systems, where \(M_{LMXB}/M_{CV} \sim 10\), the longer orbital periods and the final larger values of \(R\) make this ratio of order unity. We conclude that intrinsic LMXB superhumps have luminosities \(L_{sh}\) similar to those in CVs. But the latter are a fraction \(f \lesssim 0.1\) only of the total intrinsic optical disc luminosity \(L_{opt}(\text{visc})\), and the same will be true in LMXBs. Thus intrinsic superhump luminosity variations in LMXBs have amplitudes

$$
\frac{L_{sh}}{L_{irr}} = L_{sh}/L_{opt(\text{visc})}/L_{irr} < f \times 10^{-3} \lesssim 10^{-4}
$$

of the observed disc brightness resulting from irradiation. Superhump variations powered by intrinsic viscous dissipation are therefore negligible in LMXBs, and cannot explain the observed superhump amplitudes.

## 3 DISC AREA VARIATIONS

The work of the last Section shows that one can only rescue the resonance theory of superhumps for LMXBs if the
efficiency of the precessing disc in reprocessing the central X-rays varies on the superhump period. Writing

$$L_{\text{opt}} \propto A_{\text{eff}} L_X,$$

we see that this requires that the effective area $A_{\text{eff}}$ which the disc presents to the X-rays must vary on this cycle. In principle this could occur because the disc aspect ratio might vary on this cycle. Smale et al. (1992) suggest this occurs because the vertical component of gravity for the disc rim will be significantly increased when the outermost part of the elliptical disc coincides in azimuth with the mass donor star. They do not, however, present any quantitative assessment of how large an effect this will be.

In contrast, by far the simplest possibility is that the total disc surface area varies. This may indeed have been seen in observations of a persistent superhumper, V348 Pup (Rolfe et al., 2000). Moreover, SPH simulations also predict a ~ 10% variation of the area. Figure 1 shows the disc area changes found in a simulation (Murray 2000) of the dwarf nova OY Car. This simulation assumed a mass ratio $q = 0.102$, similar to those measured in black hole SXTs, and found a superhump period excess $\epsilon = 0.0295$. The maxima of the area variations are in phase with the intrinsic viscous dissipation maximum, while the area minima lag the dissipation minimum by about 45 degrees. From $\epsilon$ we see that the area variations of Fig. 1 give approximately the predicted optical light curve, apart from the effect of dilution by other sources of optical emission. The most important of these is the X-ray heated face of the secondary star, whose effective temperature $T_{\text{eff}}$ we can crudely estimate from

$$T_{\text{eff}}^4 \sim \frac{\eta M c^2 (1 - \beta)}{4 \pi \sigma a^2} \frac{R_2^3}{4a^2},$$

and grazing eclipses (Zurita et al 2000). There was no trace of a superhump modulation, but this is to be expected for a neutron star system with $P_{\text{orb}} = 6.0$ hr, since the mass ratio is unlikely to satisfy (1).

4 DISCUSSION

We have shown that variations of the disc surface area on the superhump cycle offer a plausible explanation for the superhump light curves observed in LMXBs. The superhump modulation in area (Figure 1) shows that the geometry of the accretion flow varies on the superhump period. Therefore: (i) the area of the disc visible to the observer changes, causing a modulation in the optical flux; (ii) the solid angle the disc subtends at the X-ray source will probably change, causing a modulation in the intercepted fraction of $L_X$. Both these factors contribute to the superhump modulation.

The small observed values of $\epsilon$ are a natural consequence of the extreme mass ratios $q$ and high disc temperatures in LMXBs. The incidence of detected superhump variations, currently unambiguously seen in 2 or 3 SXTs, is in line with expectations from this model, as data able to address the issue was not collected for most SXTs. If the disc had any front–back asymmetry, perhaps as a result of warping under radiation–induced torques (Pringle 1996, Wijers and Pringle 1999), detection of optical modulation on the disc precession period $P_{\text{pre}}$ might be possible. However the small observed $\epsilon$ values mean that $P_{\text{pre}}$ is of order 10s of days, and thus frequently comparable with the duration of the outburst itself. Since neither $P_{\text{orb}}$ nor $P_{\text{pre}}$ will in general be known until the outburst has finished, this highlights the importance of obtaining accurate photometry of any ‘orbital’ variations at as many stages of an outburst as possible.

In SXTs we can establish $P_{\text{orb}}$, accurately from radial velocity measurements in quiescence, and thus confidently say whether a given photometric modulation is or is not a superhump. In a persistent LMXB, it is generally only possible to determine $P_{\text{orb}}$ if the system is at high orbital inclination so that X-ray eclipses or dips are seen as the central source is periodically occulted by the mass donor star or vertical structures in the disc rim. Of the five possible LMXB superhumpers listed in Ritter and Kolb (1998) four are SXTs. The
fifth is the dipping source V1405 Aql which was originally suggested as a possible superhumer by White (1989). We discuss this source and GX 9+9 individually, before giving a general discussion.

4.1 V1405 Aql (A 1916-05, 4U 1915-05)

V1405 Aql was comprehensively studied by Callanan, Grindlay and Cool (1995, hereafter CGC). Their observational findings were

(i) the optical period is 50.4589 mins
(ii) the X-ray period is 50.00 mins
(iii) in an “anomalously low optical state” (0.5 mag below normal) both 50.46 and 50.00 min periods were observed in the optical
(iv) the 50.4589 min period seems to have phase stability over 7 years.

CGC’s conclusions were first that 50.4589 mins is the orbital period $P_{\text{orb}}$, since the superhumps in outbursting SU UMa stars show neither period nor phase stability over weeks, let alone years. Second, in the anomalously low optical state the intrinsic (i.e. viscously generated) brightness of the disc should make a significant contribution, rendering “SU UMa - like precessing behaviour” more observable. Finally phase-wandering of the optical dips when folded on the X-ray period prevents simple interpretation of the periodicities.

Since 1915-05 is a steady X-ray source, it is misleading to compare it with the SU UMa CVs in which the disc is subject to the thermal-tidal instability. SU UMa stars exhibit superhumps during their outbursts, when their discs are in the high viscosity state for days to weeks. SU UMa discs therefore change their radii and mass distributions on timescales of days, and their superhumps evolve as a consequence of this. For a steady disc satisfying equation (1) we should expect the superhumps to settle into a stable oscillation: simulations of precessing eccentric discs settle into periodic behaviour unless the boundary conditions change (Murray 1998, Whitehurst private communication). We conclude that the phase stability of the 50.4589 min period is no barrier to interpreting it as $P_{\text{sh}}$. We accordingly identify the 50.00 min period as $P_{\text{orb}}$.

The ratio of viscously-generated to irradiation-generated flux remains constant (equation 2), unless either the disc is gaining or losing mass at some radius, or the geometry changes. In fact all the non-negligible components of the optical light curve: $L_{\text{acc}}, L_{\text{irr}},$ and the irradiated flux from the mass donor, remain in the same ratios for a steady state accretion flow with any $M$ unless the geometry changes. Therefore it is likely that CGC’s “anomalously low optical state” coincides with a change in the geometry of the accretion flow, making irradiation of the mass donor star more prominent. If the geometry did not change there would be no reason for the modulation at $P_{\text{orb}}$ to become more prominent (the ellipsoidal variation would introduce a signal at $P_{\text{orb}}/2$, but is never likely to be observable as the intrinsic flux from the mass donor is certain to be negligible in a short period X-ray-emitting neutron star binary like V1405 Aql).

Since we are proposing that the geometry of the disc changes on $P_{\text{sh}}$, the deep dips seen in figure 7 of CGC could well be analogous to the “superdip” seen in OY Car by Billington et al (1996). This interpretation can also explain the phase-wandering of the optical dips when they are folded on $P_{\text{orb}} = 50.00$ mins, hence negating the third of CGC’s conclusions.

We identify V1405 Aql as a persistent irradiated superhumper. With our interpretation $\epsilon = 0.009$, and the inferred period of apsidal disc precession is $P_{\text{precc}} = 3.8$ days. Interestingly, the shape of the optical light curves was found to be modulated on a $\sim 4$ day period (Smale et al 1989). Homer et al (2000) have extensive X-ray and optical data which seem consistent with our interpretation and with warping of the disc. Nodal precession of a warped disc may introduce further observable periodic modulations, analogous to the 35 day period in Her X-1 (Scott & Leahy 1999), and may be responsible for the 199 day cycle in 4U 1915-05 reported by Smale (1994).

4.2 GX 9+9 (4U 1728-16, Oph X-1, 2S 1728-169)

This system was suggested as a possible persistent superhumer by Haswell and Abbott (1994) who found a $4.1744 \pm 0.0002$ hr modulation in I band photometry. Schaefer (1990) had previously reported a B band modulation of period $4.19 \pm 0.028$ hr, and Hertz and Wood (1988) found an X-ray period of $4.19 \pm 0.02$ hr. These periods are clearly all mutually consistent. With $P_{\text{orb}} = 4.2$ hrs and a neutron star primary, the system has a mass ratio $q < 0.28$ (Schaefer 1990) satisfying (1), since the secondary mass $M_2$ cannot exceed the mass $\sim 0.5M_\odot$ of a main-sequence star filling the Roche lobe (see below). We should therefore expect GX 9+9 to harbour a persistently precessing elliptical disc. The $\sim 10\%$ fractional amplitude of the optical modulations in GX 9+9 is similar to those reported by O’Donoghue and Charles (1996) for the superhumps in SXTs, and the changes in the shapes of the optical light curves shown in Haswell and Abbott (1994), figure 3, are suggestive of a light curve shape modulation at $P_{\text{precc}}$.

Since there are extensive RXTE observations of this source in hand, a more precise X-ray period is likely to soon be available. Clearly this, and more extensive optical photometry is required to test our hypothesis that GX 9+9 is an irradiated disc persistent superhumper. Kong et al (2000) will address this.

4.3 Many LMXB superhumpers?

Table 1 lists LMXBs in order of increasing $P_{\text{orb}}$ as reported in the literature. The third column in this table gives the nature of the modulation leading to the $P_{\text{orb}}$ determination. For the eclipsing systems and those in which orbital motion has been measured (denoted either “opt RV” for mass donor radial velocity modulations or “pulsation RV” for pulse timing modulations) $P_{\text{orb}}$ is securely determined. The remaining 17 period determinations arise from modulations in X-ray, UV, or optical flux and cannot be identified as $P_{\text{orb}}$ with certainty; these 17 periods are in boldface.

We can show that the condition (1) for superhumps is likely to hold for the first 11 systems listed in Table 1. The accreter presumably cannot be less massive than a neutron star, and indeed is known to be such a star in the first 10 cases because of the presence of X-ray bursts. Accordingly
we can assume that \( M_1 \gtrsim 1.4M_\odot \). The likely candidates for the donors are either main-sequence stars, satisfying \( M_2 \approx 0.11P_{\text{orb}}^{-1}M_\odot \) (e.g. King, 1988), or degenerate stars, obeying \( M_2 \approx 0.015(1 + X)^{5/2}P_{\text{orb}}^{-1}M_\odot \) (King, 1988) where \( X \) is the fractional hydrogen content by mass. (Degenerate companions are likely in the 5 systems in Table 1 with \( P_{\text{orb}} \leq 1 \).) We thus find

\[
q_{\text{MS}} \leq 0.079P_{\text{hr}}, \quad q_{\text{deg}} \leq 0.0115(1 + X)^{5/2}P_{\text{hr}}^{-1},
\]

(10)

for the two cases, showing that indeed the condition (1) for superhumps holds for \( P_{\text{orb}} \lesssim 4.2 \) hr. The only possible exception to this would be a donor star which has undergone thermal-timescale mass transfer, as is thought to have occurred in for example Cygnus X-2 (King & Ritter, 1999). These stars are stripped down to their denser central regions, and have larger masses when filling the Roche lobe at a given period. However it is unlikely that periods \( \lesssim 2 \) hr are accessible to this kind of evolution (King et al., 2000).

Accordingly we expect that for the lower inclination systems with \( P_{\text{orb}} \lesssim 4.2 \) hr, an optical or UV modulation is more likely to be a superhump than an orbital modulation. For high inclination systems satisfying (1) it is possible that the X-ray dip behaviour depends on the disc’s precession and superhump cycles, rather than straightforwardly indicating \( P_{\text{orb}} \).

For a very extreme mass ratio, \( q < 0.02 \), the circularization radius, \( R_{\text{circ}} \), is bigger than the 3:1 resonance radius (cf Frank et al. 1992, eqns (4.17, 5.75); Warner 1995 eqn (2.4a)). In this case we expect the disc to show persistent superhumps for all values of \( M \). An LMXB with a 10M\odot black hole primary and a secondary \( \lesssim 2M_\odot \) would satisfy this, and have \( P_{\text{orb}} \approx 2 \) hr.

If it were possible to show unambiguously that an LMXB with \( P_{\text{orb}} > 5 \) – 7 hr exhibited superhumps, this would suggest it harboured a black hole primary. We note, of course, that superhumps alone cannot provide proof of a black hole primary, as the secondary could have lower mass than a main sequence star, for example if it were slightly evolved. This might allow superhumps even though the primary was a neutron star. However, coupled with a lack of Type I X-ray bursts, and with the presence of X-ray spectral and timing indicators of black hole candidacy, this line of argument could prove useful, since it it extremely difficult to obtain a dynamical mass determination for the accretor in a persistent LMXB. It is notable that all the identified black holes among LMXB primaries (denoted BH in Table 1) are in transient systems. The nature of the compact objects in steady LMXBs which neither pulse nor burst is currently an undesirably open question.

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**Table 1.** Properties of LMXBs, adapted from Charles (1998), van Paradij(1995) and van Paradijs (1998)

| Source          | Period (hrs) | Nature of modulation | X-ray type      |
|-----------------|-------------|----------------------|-----------------|
| X1820-303       | 0.19        | X-ray                | Burster, glob.cl.|
| 4U 1850-087     | 0.34        | UV                   | Burster, glob.cl.|
| X1626-673       | 0.7         | opt sideband         | Burster, Pulsar  |
| X1832-330       | 0.73        | UV                   | Burster, glob.cl.|
| X1916-053       | 0.83        | X-ray, opt           | Burster, Dipper |
| J1808.4-3658    | 2.0         | pulsation RV         | Burster, Pulsar, Transient |
| J1323-619       | 2.9         | X-ray dip            | Burster, Dipper |
| X1636-536       | 3.8         | opt                   | Burster          |
| X0748-676       | 3.8         | eclipsing            | Burster, Dipper, Transient |
| X1254-690       | 3.9         | X-ray dip            | Burster, Dipper |
| X1728-169       | 4.2         | opt                   | Burster          |
| X1755-338       | 4.4         | X-ray dip            | Dipper           |
| X1735-444       | 4.6         | opt                   | Burster          |
| J0422+32        | 5.1         | opt RV               | BH, Transient   |
| X2129+470       | 5.2         | opt                  | ADC, Transient  |
| X1822-371       | 5.6         | eclipsing            | ADC             |
| J2123-058       | 6.0         | eclipsing            | Burster, Transient |
| N Vel 93        | 6.9         | opt RV               | BH, Transient   |
| X1658-298       | 7.2         | X-ray dip            | Burster, Dipper |
| A0620-00        | 7.8         | opt RV               | BH, Transient   |
| G2000+25        | 8.3         | opt RV               | BH, Transient   |
| A1742-289       | 8.4         | eclipsing            | Burster, Transient |
| X1957+115       | 9.3         | opt                   | BH, Transient   |
| N Mus 91        | 10.4        | opt RV               | BH, Transient   |
| N Oph 77        | 12.5        | opt RV               | BH, Transient   |
| Cen X-4         | 15.1        | opt RV               | Burster, Transient |
| X2127+119       | 17.1        | eclipsing            | Burster, ADC, glob.cl. |
| Aql X-1         | 19          | opt                   | Burster, Transient |
| Sco X-1         | 19.2        | opt                   | Prototype LMXB  |
| X1624-490       | 21          | X-ray dip            | Dipper           |
| V404 Cyg        | 155.4       | opt RV               | BH, Transient   |
| 2S0921-630      | 216         | eclipsing            | ADC             |
| Cyg X-2         | 235         | opt RV               | Burster          |
| J1744-28        | 283         | pulsation RV         | Burster, Pulsar, Transient |

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