The nature of the compact object in quiescent SXTs

F. K. Sutaria*, U. C. Kolb†, E. Kuulkers**, P. Charles‡ and S. Chaty§

*Indian Institute of Astrophysics., Bangalore, India
†The Open University, Dept. of Phys. and Astronomy., U.K.
**ESA-ESAC, Spain
‡University of Southampton, U.K.
§Laboratoire AIM, CEA/DSM - CNRS- UniversitĂľ Paris Diderot, France.

Abstract. We report on the observation of two quiescent stage Soft X-ray transients – the BH-SXT GS1124-68 and the NS-SXT J2123-058.

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INTRODUCTION

Soft X-ray transients (SXTs) are low mass X-ray binaries (LMXBs) consisting of a neutron star (NS) or a black hole (BH) primary, undergoing accretion from a Roche-lobe filling, low-mass, secondary. Occasionally, these systems undergo non-periodic outbursts (over intervals of 1-60 yr), reaching maximum X-ray luminosities of $L_o \sim 10^{37}$ to 10^{38} ergs s^{-1}. In quiescence, however, these sources can be as faint as $L_{quies} \sim 5 \times 10^{31}$ for NS-SXTs (SAX 1808.4-3658 [Campana et al. 2002]) and $L_{quies} \sim 10^{30.5}$ for BH-SXTs. X-ray emission in the quiescent state is most likely determined by the nature of the primary. Since most SXTs are detected while in quiescence, one aim of the study of quiescent systems with known primaries (BH or NS) is to seek a spectral or a luminosity signature, by which the nature of the unknown accretor in other SXTs can be unambiguously determined.

While the origins of quiescent state X-ray emission are still uncertain, the detection of Type-I X-ray bursts [Chen et al. 1997], which are signatures of thermonuclear explosions, in NS-SXTs in outbursts, suggests that quiescent emission from these objects is most probably thermal emission from surface of the cooling NS. The core and deep inner crust of the NS are assumed in this model to act as heat reservoirs for a fraction of the energy released in the outburst phase, through thermonuclear burning, e^{-}-captures and pycnonuclear reactions in the inner crust ([Brown et al. 1998],[Heinke et al. 2003] and references therein). If so, observations of quiescent NS-SXTs would determine the radius R_{NS}, which, coupled with independent determination of mass M_{NS} (from the mass function) during outburst phase, could finally allow us to determine the NS equation of state.

NS-SXTs and BH-SXTs in quiescence show a correlation between $\log L_{quies}$ vs orbital period P_{orb}, with NS-SXTs being a factor of ~ 100 brighter than BH-SXTs with a similar P_{orb} ([Garcia et al. 2001], [1] and references therein]. In BH-SXTs, the lower

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X-ray luminosity is attributed to an advection dominated accretion flow (ADAF), which carries matter and energy from the outer, thin accretion disk, into and beyond the event horizon. In this case of a NS-SXT, the hot NS also re-radiates the energy transmitted to it via the ADAF. Finally, recent studies in IR and radio bands suggests that BH and NS may channel different fractions of the total accretion power into relativistic outflows, with substantially reduced jet contribution in a quiescent NS system, as compared to a BH system [Gallo et al. 2008].

We present below XMM-Newton observations of two SXTs: the BH-SXT GS1124-68 and the NS-SXT J2123-058. GS1124-68 is a 10.4 hr binary at a distance $d = 5.5$ kpc, with $M_{BH} = 6.95 \pm 0.6 M_{\odot}$, which has been in quiescence since an outburst during Jan. 9-11, 1991 ([Sutaria et al. 2003] and reference therein). J2123-058 is at $d = 9.6$ kps, with $P_{orb} = 5.9562$ hr. The detection of QPOs during outburst implied NS spin period of 3.92 ± 0.22 ms, (Tomsick et al. 1999, and [Sutaria et al. 2008]). It has been in quiescence since June 1998.

OBSERVATIONS AND DATA ANALYSIS

A detailed analysis of the Feb 24-25, 2001 XMM-Newton observation of GS1124-68 in quiescence is given in [Sutaria et al. 2003]. We detail here the 32.1 ks long, Oct. 25, 2003, observation of J2123-058 in quiescence.

We used the pipeline processed data for this source. The EPIC-PN and EPIC-MOS1 and-MOS2 data were filtered using the SAS-xmmselect task, and parameters recommended by "the user's guide to the XMM Newton Science analysis system". Since the XMM-Newton EPIC CCDs are subjected to occasional flares of high energy particles (mainly protons), which contribute to the background, removal of these contaminants reduced the good-time interval to 19.1 ksec in EPIC-PN.

The source is very faint, with a background subtracted count-rate of $2.9(\pm 0.76) \times 10^{-3}$ counts/s (0.3-10.0 keV), in EPIC-PN. The corresponding count rates in EPIC MOS1 and MOS2 were $1.62(\pm 0.34) \times 10^{-3}$ counts/s and $0.98(\pm 0.29) \times 10^{-4}$ counts/s respectively. Details of data extraction and analysis are given in [Sutaria et al. 2008].

The extracted spectra and light curves were analysed with the XSPEC (version 11.3.0), using the Cash statistic relevant to data with low counts. A combined analysis of the MOS1, MOS2 and EPIC-PN data resulted in relatively poorer constraints on the fitted spectral parameters. Hence, we fitted only the 0.2-10.0 keV EPIC-PN data to the simple power-law model, the disk black body, the thermal bremsstrahlung model and the Neutron Star with hydrogen Atmosphere (NSA) models (see Tab. 1). Because the source is very faint, it was deemed necessary to keep the column density N_H constant in order to ensure a reasonable fit to the data. We use here $N_H = 0.59 \times 10^{21}$ cm^{-2}, as predicted for this region of the sky from the Bell Survey of HI regions in the galaxy [Stark et al. 1992]. Using $N_H = 0.573 \times 10^{21}$ cm^{-2}, as deduced from the RXTE observations in outburst [Tomsick et al. 1999] did not change the results within statistical limits.

Details of the fitted parameters, the absorbed flux and the unabsorbed luminosity (at $d = 9.6$ kpc) are given in Tab. 1. The best fit is obtained by assuming that the source, at a fixed distance $d = 9.6$ kpc, is radiating like a NSA. The effective temperature and corresponding luminosity, assuming that the source is at infinity, are $T_{eff}^{\infty} = g_r T_{eff} =$

TABLE 1. Spectral analysis of EPIC-PN data in the 0.2-10.0 keV range for SXT J2123-058. $N_H = 0.59 \times 10^{21}$ cm^{-2} is constant throughout. α is the photon index, $\log T_{\rm eff}$ ($T_{\rm eff}$ in K) is the effective temperature from the NSA models, while kT (in keV) is the black body temperature, the temperature of the inner edge of the accretion disk, or the plasma temperature, as the case may be, for the non-NSA models. $f|_{0.3-10.0}$ is the absorbed flux in the 0.3-10.0 keV band, while $L_{qules}|_{0.3-10.0}$ is the unabsorbed quiescent luminosity, calculated for a distance of 9.6 kpc. Fit (a) for the NSA model allows the distance D to vary, while fit (b) keeps D=9.6 kpc as constant.

Model	α	$\log T_{\rm eff}$	kT keV	CASH M.C. Prob.	$f\|_{0.3-10.0}$ $\times 10^{-15}$ ergs cm^{-2} s^{-1}	$L_{quies}\|_{0.3-10.0}$ $\times 10^{31}$ ergs s^{-1}
NSA fit (a)	–	$5.9^{+0.1}_{-0.1}$	–	35 %	6.46	11.7
NSA fit (b)	–	$5.9^{+0.02}_{-0.03}$	–	52.6 %	6.38	11.7
Powerlaw	$3.4^{+0.7}_{-0.6}$	–	–	45%	8.2	15.5
Powerlaw+ NSA	$3.13^{+0.9}_{-0.8}$	$5.0^{+2.0}_{-0.0}$	–	40.8 %	8.14	15.9
Black Body	–	–	$0.14^{+0.03}_{-0.01}$	28.7 %	6.3	10.9
disk black body	–	–	$0.19^{+0.07}_{-0.03}$	42.6%	6.4	11.7
thermal bremss.	–	–	$0.4^{+0.2}_{-0.1}$	41.5%	6.72	12.6

$0.052^{+.002}_{-0.003}$ keV, and $L^b_\infty = 4\pi R^2_{NS}\sigma g^2_r T^4_{eff} = 1.7^{+0.3}_{-0.4} \times 10^{32}$ ergs cm^{-2}, respectively, where the redshift factor $g_r = (1 - 2GM_{NS}/R_{NS}c^2)^{0.5}$.

DISCUSSION

In Fig. I, we plot $L_{quies}/10^{38}$, as a function of P_{orb}. An identical value of P_{orb} implies that the binaries are at similar stages of evolution, and hence have similar mass transfer rates $\dot{M}_T$. A certain correlation between quiescent luminosity and orbital period does appear to exist, though the large distance uncertainties, especially to BH-SXTs, (e.g. $d \sim 2.8$ to 5.5 kpc for GS1124-68), could certainly have introduced (or suppressed) a clear separation. Further, the existence of a minimum L_{qudes} is expected because below $P_{orb} \sim 10$ to 12 hr, $\dot{M}_T$ is gravitational wave (orbital angular momentum loss) driven, and hence increases with decreasing P_{orb}, while above that value $\dot{M}_T$ is decided by the nuclear evolution of the secondary, and hence $\dot{M}_T$ increases with increasing P_{orb}. Yet another caveat to the apparent $L_{quies} - P_{orb}$ correlation is the non-detection of the quiescent NS-SXT 1905+000, which, with a limiting luminosity of 2.4×10^{30} ergs s^{-1}, is fainter than the faintest BH-SXT A 0620-00 ($L_{quies} = 3 \times 10^{30}$ ergs s^{-1}) [Jonker et al. 2008]. We note that quiescent stage X-ray emission is unlikely to originate from the corona of the secondary as thermal plasma (Raymond-Smith) model is a poor fit to our data for both GS1124-68 and J2123-058.

Our detection of NS-SXT J2123-058 confirms the upper limit set on this source by the 13 Nov 2002 Chandra observation [Tomsick et al. 2004]. At $L_{quies} = 8.15 \times 10^{31}$

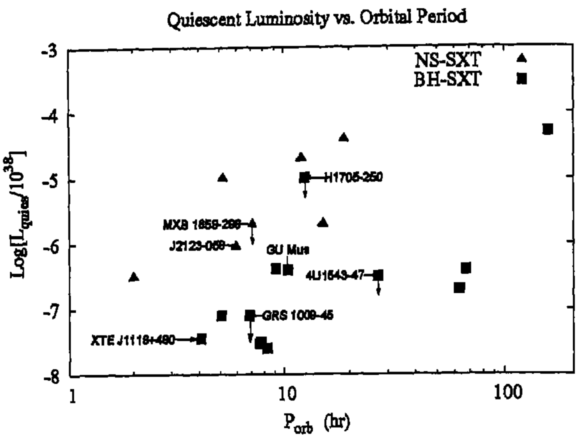

FIGURE 1. Luminosity vs. Orbital period plot for NS- and BH-SXTs in quiescence. Data from [Sutaria et al. 2003], [Garcia et al. 2001], [Tomsick et al. 2003], [Gallo et al. 2008] (XTE J1650-500) and present work.

ergs s^{-1} (for $d = 9.6$ kpc), this object is only a factor of ~ 10 brighter than the BH-SXT GRO J0422+32, which has the closest P_{orb} at 5.1 days. J2123-058 has a relatively low L_{quies}, as well as a low outburst bolometric luminosity ($L_o = 1.9 \times 10^{37}$ ergs s^{-1} in $2-12$ keV range, [Tomsick et al. 1999], [Casares et al. 2002]. Both the outburst and quiescent properties are consistent with other faint NS-SXTs, including SAX J1810.8-2609 and the accreting millisecond X-ray pulsar SAX J1808.4-3658 [Jonker et al. 2004]. If the bolometric luminosity is due to a cooling NS, then, assuming that the core and the crust have reached a steady state and that all standard cooling processes hold true, and using the relations described in [Brown et al. 1998], we estimate the recurrence time of of an outburst to be 10-100 yr, and the time averaged accretion rate (taken over both outburst and quiescence) would be $\sim 4.6 \times 10^{-12}$ $M_{\odot}$ y^{-1}.

Finally, the fact that a power law model is also a good fit to our data, prompts us to examine two other possible emission models: (a) the power-law may be generated by an ADAF, [Menou et al. 1999], in which case we should also expect to see a soft component due to the accretion disk itself. Otherwise,(b) a power-law could be generated by the interaction of the relativistic particles in the pulsar wind with matter lost from the secondary [Campana et al. 1998], though we should also expect to see a thermal component from the cooling NS in that case. Case (b) also requires the "switching on" of the radio pulsar after the outburst stage accretion has ceased, and none has been detected so far. We also note here that a combined power-law + NSA model did not improve the fit – though this may be due to the low number of counts.

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