X–RAY TRANSIENTS IN QUIESCENCE

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ABSTRACT Transient X–ray binaries remain in their quiescent state for a long time (months to hundred years) and then bright up as the most powerful sources of the X–ray sky. While it is clear that, when in outbursts, transient binaries are powered by accretion, the origin of the low luminosity X–ray emission that has been detected in the quiescent state has different interpretations and provides the unique opportunity for testing different accretion regimes. In this paper we concentrate on the various aspects of the accretion physics at low rates onto compact objects. We describe the observational panorama of quiescent emission for the three classes of X–ray transients and try to interpret these data in light of the different regimes accessible at such low mass inflow rates.

KEYWORDS: X–ray: stars – Accretion, accretion disks – Black hole physics – Stars: neutron

1. INTRODUCTION

X–ray transients are classified based on their outburst spectral properties (e.g. White et al. 1984): hard X–ray transients (HXRTs), soft X–ray transients (SXRTs) and ultra soft X–ray transients (USXRTs). This classification is successful since it reflects the true nature of these systems: HXRTs host a high magnetic field neutron star (NS) accreting from a high mass, usually Be, companion star (for a review see Bildsten et al. 1997); SXRTs host a low field NS accreting from a late type, usually K-M, star (e.g. Campana et al. 1998a) and USXRTs consisting of a black hole candidates (BHCs) accreting from a low mass companion too (e.g. Tanaka & Shibazaki 1996). Transient binaries are characterised by an X–ray luminosity that varies over many orders of magnitude, allowing to probe different conditions and accretion regimes that are unaccessible to persistent (bright) sources.

In this paper I will first review the observational properties of transient X–ray sources and then challenge these with simple theoretical models.

\footnote{Here I consider only sources containing fastly spinning NS (P \(\lesssim\) 10 s), which share several properties with SXRTs.}
2. BLACK HOLE TRANSIENTS

BHCs are usually faint in their X-ray quiescent state and strong upper limits exist for a number of them (Menou et al. 1999; Campana & Stella 2000). The first, and only short orbital period (7.8 hr), BHC detected in quiescence to date is A 0620–00. This is the prototype BHC: after a very bright outburst peaking at \( \sim 7 \) Crab, the source slowly returned to quiescence and only ROSAT, years later, was able to reveal it. The 0.1–2.4 keV luminosity is \( \sim 6 \times 10^{30} \) erg s\(^{-1}\) (for a distance of 1.2 kpc and by fixing the column density to \( N_H = 1.2 \times 10^{21} \) cm\(^{-2}\); McClintock et al. 1995). Due to the small number of photons (\( \sim 40 \)) however, the spectrum is very poor and can be well fit by a variety of single component models. In particular, it cannot be excluded that such a low luminosity arises from the K dwarf companion (see also Bildsten & Rutledge 2000).

The other two BHCs detected in quiescence are characterised by longer orbital periods (\( > 2.5 \) d) and therefore higher average mass inflow rates, based on evolutionary models. GS 2023+338 (V 404 Cyg) was detected at \( L \sim 2 \times 10^{35} \) erg s\(^{-1}\) with ASCA and BeppoSAX (Narayan et al. 1997; Campana et al. 2000c). The spectrum is well fit by either a power law (photon index \( \Gamma \sim 1.5 - 2 \)) or a bremsstrahlung (\( k T_{br} \sim 5 - 10 \) keV). GRO J1655–40 was detected at \( L \sim 2 \times 10^{32} \) erg s\(^{-1}\) (Hameury et al. 1997), with a spectrum that can be described by a power law model with \( \Gamma \sim 1.5 \).

2.1. ADAF

The very low luminosity of BHCs in quiescence has stimulated a number of works. The paradigm is now represented by advection-dominated accretion flow (ADAF) models, where the radiative efficiency is very low (\( \sim 10^{-4} \) – \( 10^{-3} \)) and most of the gravitational energy of the inflowing matter is stored as thermal and/or bulk kinetic energy and advected towards the collapsed star (e.g. Narayan et al. 1996; Narayan et al. 1997; Menou et al. 1999). Solutions of this type exist for sub-Eddington mass accretion rates (\( \dot{M} < 0.1 - 0.01 \dot{M}_{\text{Edd}} \)). In this regime the bolometric luminosity scales approximately as \( \dot{M}^2 \) (as opposed to the \( \dot{M} \) scaling of standard accretion; cf. Fig. 1). These models (which where modified under way to include the optical/UV luminosity as produced by the ADAF itself; cf. Narayan et al. 1997) provide good fit to the multi-wavelength spectra of quiescent BHCs.

3. HARD X-RAY TRANSIENTS

Despite a considerable increase in the number of new HXRTs discovered in the last few years thanks to RXTE, observational data on the transition to quiescence of HXRTs are still sparse. For only a few systems (V 0332+53 Stella et al. 1986; 4U 0115+63 Tamura et al. 1992) there were indications of a sudden turn off of the X-ray luminosity when the sources achieve a level of \( \sim 10^{36} \) erg s\(^{-1}\).

Even more rare are the observations of HXRTs in quiescence. In the last few years, only the HXRT A 0538–66 in the Large Magellanic Cloud (containing the
FIGURE 1. Luminosity versus the mass inflow rate (in Eddington units \( \dot{M} \sim 1.4 \times 10^{18} \frac{M}{M_\odot} \text{g s}^{-1} \)) for different accretion regimes onto BHs and NSs. The upper line refers to a 14 \( M_\odot \) BH. The dashed line marks the standard accretion regime (efficiency \( \epsilon = 0.1 \)) and the continuous line the ADAF model. The lower lines refer to accretion onto a 1.4 \( M_\odot \) NS. The continuous line gives the luminosity produced by a 2.5 ms spinning, \( B = 10^8 \) G NS in different regimes, the dotted line by a 4 s, \( B = 10^{12} \) G NS. The lower dashed line refers to accretion onto the NS surface.

fastest accreting NS at 69 ms) has been positively detected in quiescence. During the ROSAT all-sky survey two weak outbursts were detected, with peak luminosities of \( \sim 4 \) and \( \sim 2 \times 10^{37} \) erg s\(^{-1}\) in the 0.1–2.4 keV range (Mavromatakis & Haberl 1993) and a similar weak outburst was detected by ASCA at \( \sim 6 \times 10^{36} \) erg s\(^{-1}\) (1–10 keV; Corbet et al. 1997; Corbet 1996). A 0538–66 was detected several times at a level of about \( 10^{34} \)–\( 10^{35} \) erg s\(^{-1}\) during ROSAT PSPC serendipitous pointings (Campana 1997). ASCA and ROSAT observations gave a first indication of the spectrum at such low rates: the ASCA spectrum is well fit by a power law (photon index \( \Gamma \sim 2 \)) plus a soft component, e.g. a black body with temperature \( \sim 3 \) keV and equivalent radius of \( \sim 2 \) km. The ROSAT PSPC spectrum at a factor of 10–100 lower luminosity can be fit by a black body model with much smaller temperature (\( \sim 0.2 \) keV) and larger radii (\( \sim 70 \) km). The presence of a hard power law however cannot be excluded. Recently, we obtained BeppoSAX observations of three fast spinning HXRTs (A 0538–66, V 0332+53 and 4U 0115+63) during their quiescent states (Gastaldello et al. 2000). The most striking results comes from the observation
of 4U 0115+63. A 15 hr BeppoSAX observation shows a variation in the count rate by a factor of $\sim 250$ (cf. Fig. 2; Campana et al. 2000a). A time-resolved spectral analysis reveals that this variation is intrinsic to the source, which does not change its spectrum (hard power law with photon index $\Gamma \sim 1$) nor its column density (a few $10^{22}$ cm$^{-2}$, washing out any soft component). The mean 0.1–200 keV luminosity in each interval varies from $\sim 2 \times 10^{34}$ erg s$^{-1}$ to $\sim 2 \times 10^{36}$ erg s$^{-1}$ (at 4 kpc). Pulsations were detected all the way down to the smaller fluxes.

### 3.1. Propeller regime

In the relatively slow ($P \geq 1$ s) and high magnetic field ($B \sim 10^{12}$ G) NSs of HXRTs accretion onto the surface can take place as long as the magnetospheric radius ($r_m$, at which the NS magnetic field starts dominating the motion of the infall matter) is smaller than the corotation radius ($r_{\text{cor}}$, at which matter in Keplerian rotation orbits at the same angular frequency of the NS). In this regime, the accretion luminosity is given by $L(R) = G M M / R$. As the mass inflow rate decreases, $r_m$ expands till it reaches the corotation radius. For smaller rates, matter getting attached to the NS field lines at $r_m$ experiments a centrifugal force stronger than gravity and gets expelled. The source starts to be centrifugally inhibited (propeller regime) at a
luminosity of $L_{cb}$

$$L_{cb} \simeq 2 \times 10^{36} B_{12}^2 M_{1.4}^{-2/3} R_6^5 P_{4s}^{-7/3} \text{ erg s}^{-1}$$

$$\simeq 5 \times 10^{35} B_8^2 M_{1.4}^{-2/3} R_6^5 P_{2.5\text{ms}}^{-7/3} \text{ erg s}^{-1}$$  \hspace{1cm} (1)$$

$(B = 10^{12} B_{12} \, \text{G} - B = 10^8 B_8 \, \text{G}, \, P = 4P_{4s} \, \text{s} - P = 2.5 \times 10^{-3} P_{2.5\text{ms}} \, \text{s}, \, R = 10^6 R_6 \, \text{cm and} \, M = 1.4 M_{1.4} M_\odot$ are the magnetic field, spin period, radius and mass of the NS, respectively). Matter, being stopped at $r_m$ rather than $R$, releases a lower accretion luminosity. The accretion luminosity gap, $\Delta_c$, across the centrifugal barrier is (Corbet 1996; Campana & Stella 2000)

$$\Delta_c \simeq \frac{r_{cor}}{R} = \left( \frac{G M P^2}{4 \pi^2 R^3} \right)^{1/3} \simeq 620 P_{4s}^{2/3} M_{1.4}^{1/3} R_6^{-1} \simeq 3 P_{2.5\text{ms}}^{2/3} M_{1.4}^{1/3} R_6^{-1}. \hspace{1cm} (2)$$

$\Delta_c$ depends almost exclusively on the spin period $P$ and is basically a measure of how deep $r_{cor}$ is in the potential well of the NS.

This simple picture is challenged by the recent observations of 4U 0115+63. The centrifugal gap that has been modeled as a step-like transition from the accretion to the propeller (or vice versa) regimes has likely been observed. Assuming a typical mass inflow rate variation as derived from BeppoSAX observations of 4U 0115+63 in outburst, one can derive a relation between the observed luminosity and the mass accretion rate $L \propto \dot{M}^\alpha$ which in the case of standard accretion implies $\alpha = 1$ and in the propeller $\alpha = 9/7$. We derive a value of $\alpha \sim 30$, indicating that a very small variation in $\dot{M}$ induces a huge variation in luminosity. As a confirmation of this, disk and wind accretion model for a system like 4U 0115+63 allows for a mass inflow rate variation by a factor of a few in 15 hr, at most (e.g. Raguza & Lipunov 1998).

At variance with simple model predictions, X-ray pulsations are detected all the way down the lower part of the gap (even if with decreasing pulsed fractions). The most straightforward interpretation is that some matter still leaks the centrifugal barrier likely from the highest magnetic latitudes. We conclude that we are observing for the first time the transition from the propeller regime to the standard accretion onto the NS surface. This transition is very fast and opens the possibility to study in detail how the centrifugal mechanism works (see also Campana et al. 2000a, Pizzolato et al. 2000).

4. SOFT X–RAY TRANSIENTS

SXRTs in quiescence were the target of early X–ray astronomy missions such as Einstein (Petro et al. 1981) and EXOSAT (van Paradijs et al. 1987). These data however provide very poor spectral information. ROSAT gave for the first time a

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2We use here simple spherical accretion theory. This is a reasonably accurate approximation when the accretion disk at the magnetospheric boundary is dominated by gas pressure. For a more general approach see e.g. Campana et al. (1998a).
clear assessment in the field, revealing the SXRT prototype source Aql X-1 on three occasions at a level of $\sim 10^{33}$ erg s$^{-1}$ (0.4–2.4 keV) with a very soft spectrum (e.g. a black body with a temperature of $kT_{bb} \sim 0.3$ keV and an equivalent radius of $\sim 10^5$ cm; Verbunt et al. 1994).

The number of SXRTs detected in quiescence is now increasing thanks to BeppoSAX and ASCA: Aql X-1 (Campana et al. 1998b; Asai et al. 1998), Cen X-4 (Asai et al. 1996; Campana et al. 2000b), 4U 1608–522 (Asai et al. 1998), 4U 2129+47 and EXO 0748–676 (Garcia & Callanan 1999) and most recently SAX J1808.4–3658 (Stella et al. 2000) and X 1732–304 (Guainazzi et al. 1999). All these sources have X–ray luminosities in the $10^{32} – 10^{33}$ erg s$^{-1}$ range (e.g. Campana et al. 1998a). Together with the soft spectral component which is present in all SXRTs in quiescence observed to date (usually modeled as a black body of $kT_{bb} \sim 0.1 – 0.3$ keV), a hard power law can be revealed in the best studied sources (Aql X-1, Cen X-4 and X 1732–304). This power law (with photon index $\sim 1.5 – 2$) makes up $\sim 50\%$ of the 0.5–10 keV luminosity. This two components spectrum is becoming the ‘canonical’ spectrum for SXRTs in quiescence and further confirmations will come from Chandra and XMM-Newton pointings.

4.1. Shock emission

It had long been suspected that the NSs of persistent and transient LMXRBs have been spun up to very short rotation periods by accretion torques however, conclusive evidence has been gathered only recently. The best example is SAX J1808.4–3658, a bursting transient source discovered with BeppoSAX in 1996 (in’t Zand et al. 1998). In April 1998, RossiXTE observations revealed a coherent $\sim 401$ Hz modulation, testifying to the presence of magnetic polar cap accretion onto a fast rotating magnetic NS (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). Millisecond rotation periods have also been inferred for 7 other LMXRBs of the Atoll (or suspected members of the) group through the oscillations that are present for a few seconds during type I X–ray bursts (for a review see van der Klis 2000). Regarding the NS magnetic field, Psaltis & Chakrabarty (1999) estimate for SAX J1808.4–3658 a value of $B \sim 10^8 – 10^9$ G, by adopting different models for the disk-magnetosphere interaction. Indirect evidence for fields of $B \sim 10^8$ G derives also from the steepening in the X–ray light curve decay and marked change of the X–ray spectrum when the luminosity reaches a level of $\sim 10^{36}$ erg s$^{-1}$ in Aql X-1 (Campana et al. 1998b; Zhang et al. 1998) SAX J1808.4–3658 (Gilfanov et al. 1998), XTE 2123–058 (Tomsick et al. 1999) and Rapid Burster (Masetti et al. 2000), once these changes are interpreted in terms of the onset of the centrifugal barrier. The spin period and the inferred magnetic field strength of SAX J1808.4-3658 provide the first direct evidence for the long suspected Low Mass X–Ray Binaries millisecond pulsars connection.

As the mass inflow rate decreases further the magnetosphere expands until the light cylinder radius, $r_c = c P/2 \pi$, is reached; beyond this point the radio pulsar dipole radiation will turn on and begin pushing outward the inflowing matter, due
to a flatter radial dependence of its pressure compared to that of disk or radial accretion inflows (Illarionov & Sunyaev 1975; Stella et al. 1994; Campana et al. 1995). The equality \( r_m = r_{lc} \) defines the lowest mass inflow rate (and therefore accretion luminosity) in the propeller regime. An accretion luminosity ratio of

\[
\Delta_p = \left( \frac{r_{lc}}{r_{cor}} \right)^{9/2} \simeq 440 P_{2.5\,\text{ms}}^{3/2} M_{1.4}^{-3/2}
\]

(3)

characterises the range over which the propeller regime applies. Note that also this ratio depends mainly on the spin period \( P \).

Once in the rotation powered regime, a fraction \( \eta \) of the spin down luminosity, \( L_{sd} \), converts to shock emission in the interaction between the relativistic wind of the NS and the companion’s matter flowing through the Lagrangian point. Theoretical models indicate that the material lost by the companion star may take somewhat different shapes, ranging from a bow shock to an irregular annular region in the Roche lobe of the NS, depending on radio pulsar wind properties and the rate and angular momentum of the mass loss from the companion star (Tavani & Brookshaw 1993). \( \eta \) may be as large as 0.1 (Tavani 1991) and the shock luminosity can be expressed as \( L_{\text{shock}} = \eta L_{sd} \sim 2 \times 10^{32} \eta^{-1} B_8^2 P_{2.5\,\text{ms}}^{-4} \, \text{erg s}^{-1} \) (\( \eta \sim \eta_{-1} 0.1 \)). The luminosity ratio across the transition from the propeller to the rotation powered regime can be approximated as (Stella et al. 1994; Campana et al. 1998a)

\[
\Delta_s = \frac{3}{2 \sqrt{2\eta}} \left( \frac{r_g}{r_{lc}} \right)^{1/2} \sim 2 \eta_{-1}^{-1} P_{2.5\,\text{ms}}^{-1/2} M_{1.4}^{1/2}
\]

(4)

where \( r_g = GM/c^2 \) is the gravitational radius. The energy spectrum due to shock emission is expected to be a power law with photon index of \( \sim 1.5 - 2 \) that extends from \( \sim 10\,\text{eV} \) to \( \sim 100\,\text{keV} \), with both energy boundaries shifting as \( B_8 P_{2.5\,\text{ms}}^{-3/2} \) (Tavani & Arons 1997; Campana et al. 1998a).

Observationally, the nature of the two spectral components observed during the quiescent state of SXRTs is a matter of debate. One possibility is that some matter leaks through the centrifugal barrier accreting onto the NS surface and produces in turn the observed soft component, whereas the hard component arises in an ADAF (Zhang et al. 1998; Menou et al 1999). However a clear assessment of this spectral model has not been carried out yet, nor self-consistent ADAF models for NSs exist. The other possibility complains a cooling NS (which contributes to the soft component) working as a radio pulsar, the relativistic wind of which generates a shock power law spectrum (Campana et al. 1998a). This is, at least qualitatively, in agreement with the hard power law like X-ray component observed

\(^3\) Concerning the soft X-ray thermal-like component, we note that the effective black body radii inferred from spectral fitting are substantially smaller than the NS radius. At the same time, radiative transfer calculations for the NS atmosphere indicate that the emergent thermal-like X-ray spectrum is complex and simple black body fits are likely to underestimate the effective emission radius and overestimate the temperature by a factor of 3–10 and 2–3, respectively (Rutledge et al. 1999; Brown et al. 1998). Consequently, it cannot be ruled out yet that thermal emission from the whole NS surface powers the soft X-ray component of quiescent NS SXRTs.
in the quiescent X–ray spectrum of Cen X-4, Aql X-1 and X 1732–304. The extended power law spectrum expected from shock emission is also in agreement with the recently determined residual UV spectrum of Cen X-4, which shows no evidence for a turnover down to lowest measured UV energies (∼ 7.5 eV: McClintock & Remillard 2000) and matches quite well the extrapolation of the (power law) X–ray spectrum.

5. CONCLUSIONS

In the last few years a large wealth of new data on quiescent transient sources has been obtained thanks to BeppoSAX and ASCA. These observations give us the opportunity to study in some details the different regimes that can be expected at such low X–ray fluxes, such as the ADAF models for BHCs, the propeller regime for HXRTs and the shock emission for SXRTs. New and better data will be collected in the next few years thanks to Chandra and XMM-Newton, answering to some basic questions that are still open.

Here I list some topics that can be addressed in the next years:

- **Quiescent emission of BHCs (1).** ADAF models are now very popular in explaining the BHC quiescent emission. However these models face problems since their optical/UV luminosity (after subtraction of the contribution from the companion star) dominates by a factor of ∼ 10 over the X–ray luminosity, at variance with SXRTs in which the two luminosities are comparable, at the most. Based on the latest ADAF models, this optical/UV luminosity should be ascribed to the ADAF itself, arising from synchrotron processes. These results indicate that the luminosity swing from the outburst peak to quiescence, which has been claimed to be different in BHCs and SXRTs (Narayan, Garcia & McClintock 1997), does not provide evidence for a significant difference between the two classes. Therefore, one of the key motivations for considering ADAF models, i.e. that most of the energy is hidden beyond the BH event horizon, is considerably weakened (see Campana & Stella 2000).

- **Quiescent emission of BHCs (2).** The only short orbital period BHC detected in quiescence is A 0620–00 at a level of ∼ 10^{31} erg s^{-1} (0.5–10 keV, e.g. Menou et al. 1999). In analogy with the X–ray emission from K stars in RS CVn type binaries (which emit up to ∼ 10^{32} erg s^{-1} in the ROSAT band; Dempsey et al. 1993) one may argue that, in short orbital period BHC systems, such as A 0620–00, the low level X–ray quiescent luminosity (∼ 10^{31} – 10^{32} erg s^{-1}) might also arise from due to coronal activity of the companion star (see also Bildsten & Rutledge 2000).

- **Centrifugal gap in HXRTs.** BeppoSAX observations of 4U 0115+63 provide for the first time the opportunity to study the transition from the accretion regime to the propeller state. Good data have been obtained and their potential is being exploited, with the aim of understanding how and when the
centrifugal barrier closes (and/or opens; Campana et al. 2000a; Gastaldello et al. 2000). These data also demonstrate that the monitoring of HXRTs in quiescence, especially near periastron, is worthy.

- **Quiescent emission of SXRTs.** Two facing models have been proposed to explain the quiescent emission of SXRTs: one is based on ADAFs and included the leaking of matter through the centrifugal barrier to explain the soft X-ray component; the other one envisages the presence of an active radio pulsar. One of the most straightforward prediction of the ADAF scenario is that pulsations should be detected in the soft component. In the case of an active radio pulsar, a radio signal might be detected if the circumstellar material does not absorb completely the signal. Doppler maps can also be useful to pinpoint unusual geometries not related to an accretion disk but to a shock front.

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