Emission processes in quiescent neutron star transients

Sergio Campana

INAF – Osservatorio astronomico di Brera, Via Bianchi 46, 23807 Merate (LC), Italy

Abstract. We review the observational properties of transient systems made by a neutron star primary and a late dwarf companion (known also as Soft X-ray Transients) during their quiescent state. We focus on the several emission mechanisms proposed and try to compare them with observations. Finally, we review new tools to improve our comprehension of the physics of the emission processes.

WHAT ARE NEUTRON STAR TRANSIENTS?

Neutron star transients (also known as Soft X-ray transients, SXRTs) are binary systems with a late star companion and a neutron star primary. Orbital periods are short (less than a day) and the companion fills its Roche lobe transferring matter to the primary through the first Lagrangian point. Outflowing matter has a large angular momentum and falling onto the primary forms an accretion disk, which mediates the mass transfer. Despite persistent sources, known as Low Mass X-ray Binaries (LMXRBs), SXRTs alternate periods of quiescence, during which they attain an X-ray luminosity of $L_X \sim 10^{32} - 10^{33}$ erg s$^{-1}$ to periods (lasting weeks to months) during which they are as bright as their relatives (i.e. LMXRBs, $L_X \sim 10^{36} - 10^{38}$ erg s$^{-1}$). Actually, during these bright periods (called outbursts) SXRTs share all the same characteristics of LMXRBs. Recurrence times vary from $\sim 1$ to $> 30$ years. For a review see Campana et al. (1998a).

WHY DO WE STUDY TRANSIENTS?

Transient sources vary their luminosity over several orders of magnitude. These variations reflect, at least partially, in variations of the mass inflow rate toward the compact object and allow to sample a variety of physical conditions and regimes that are inaccessible to persistent (bright) sources. Especially interesting are SXRTs in quiescence when X-ray emission can in principle be powered by mechanisms not involving the inflow of matter onto the neutron star surface.
MEAN QUIESCENT X–RAY LUMINOSITY AND SPECTRA

The study of SXRTs in quiescence is hampered by their low luminosity. A handful of sources were known before Chandra and XMM-Newton. In particular, Chandra is discovering a large number of SXRTs in globular clusters\(^1\) (\(\sim 15\), e.g. Pooley et al. 2003), whereas XMM-Newton is providing good spectral information for a sizable number of sources. For all the sources discovered so far the quiescent 0.5–10 keV luminosity is in the range \(10^{32} \text{-- few} 10^{33} \text{erg s}^{-1}\). Only one source is outside this range and it is the first discovered millisecond transient X–ray pulsar SAX J1808.4–3658 (Wijnands & van der Klis 1998). This source has been studied through XMM-Newton observations indicating a quiescent luminosity of \(5 \times 10^{31} \text{erg s}^{-1}\) (Campana et al. 2002).

On the spectral side, common behaviors can also been found. Quiescent X–ray spectra of SXRTs are usually characterized by two spectral components: 1) a soft component modeled as a black body or, more physically, by cooling emission from the entire neutron star surface; 2) a hard power law energy tail. The first component comprises the majority of the flux (50 – 100\%). The power law tail is present only in a fraction of sources and contributes up to 50\% in the 0.5–10 keV energy band (e.g. Campana 2001).

Similarities and differences with black hole transients

Luminosities and spectra of neutron star transients are markedly different from the ones observed in quiescent transients containing a black hole (TBH) as primary. In the case of TBH the 0.5–10 keV luminosities range between \(10^{30} \text{--} 10^{31} \text{erg s}^{-1}\) (i.e. a factor of \(\sim 100\) below SXRTs) and their faint quiescent spectra show indication for the presence of only a power law tail (Garcia et al. 2001, Kong et al. 2002).

MODELS FOR THE QUIESCENT EMISSION

Several models for the quiescent emission of SXRTs have been put forward. These range from accretion of matter onto the neutron star, in several flavors (advection-dominated, convection-dominated, with outflows, etc., Menou et al. 1999, Menou et al. 2001) to jets (Fender et al. 2003), to neutron star cooling after long-term (\(10^4\) yr) heating during outbursts (Brown et al. 1998), to emission regimes connected to the presence of a magnetic field (propeller and radio pulsar turn on, Campana et al. 1998b, Campana & Stella 2000).

- Advection-dominated accretion flow (ADAF) models should naturally predict the lower X–ray luminosity observed in TBHs with respect to SXRTs (since the inner-

---

\(^1\) Actually there is a bias in these discoveries since sources are preferentially selected if they are ‘bright’ \(L_x \sim 10^{33} \text{erg s}^{-1}\) and with a soft spectrum. Recent discoveries have shown that SXRTs may also show only a hard power law tail (SAX J1808.4–3658, Campana et al. 2002; EXO 1745-248 Wijnands et al. 2003). These sources are more difficult to pinpoint due to their similarities with cataclysmic variables.
most accretion disk regions are advected inward into the black hole, whereas for neutron stars the hard surface will release all the available power). This is true only in principle and details fail to be accounted for (in particular the luminosity ratio between neutron stars and black holes quiescent luminosities of $\sim 100$, Menou et al. 1999). Moreover, the ADAF expected spectrum for SXRTs can explain only the hard part of the spectrum but not the soft component (Yu et al. 1996).

- Jet emission has been recently proposed to account for the quiescent X–ray emission of TBHs (Fender et al. 2003). This component however should be minor in the case of neutron stars.

- Cooling of the neutron star after deep crustal heating is the most popular models to explain the soft component of quiescent SXRTs. Basically, the neutron star emits black body-like radiation due to the heating of its interior occurred during the repeated outbursts (Brown et al. 1998, Colpi et al. 2001). Fitting the soft component with neutron star cooling models, several authors derived radii in agreement with the expectations (i.e. $\sim 10–15$ km) and opening the possibility of directly measuring the neutron star radii in sources of well known distances (e.g. globular cluster sources).

- Regimes related to the presence of a neutron star magnetic field involve the control of the neutron star magnetosphere of the motion of the incoming matter. When the mass inflow is large the magnetosphere is compressed and matter can reach the neutron star surface following the magnetic field lines. At lower mass inflow rates, the magnetosphere expands. For low enough rates, the magnetosphere rotates (being anchored and corotating with the neutron star) faster than the matter orbiting at Keplerian frequency around it. When matter tries to get attached to the field lines it experiments a centrifugal force larger than gravity and gets expelled. This is the propeller regime (Illarionov & Sunyaev 1975). The accretion efficiency is reduced due to the fact that matter is stopped at the magnetosphere and does not reach the surface (thus releasing less potential energy).

For even lower mass inflow rates, the magnetosphere starts rotating at the speed of light. At this point the magnetic field lines open up and the field changes from dipolar to radiative. In this situation we have a loss of energy from the rotating neutron star according to the usual Hertz formula (e.g. Campana et al. 1998a). This energy release induces a pressure on the infalling matter sweeping it away. This should be the case for quiescent SXRTs. The neutron star/radio pulsar relativistic wind interacts with matter from the companion, generating a shock front in which a fraction ($\eta \sim 0.01–0.1$, depending mainly on geometry and weakly on mass inflow rate) of the total spin-down losses. The expected spectrum is a synchrotron one with photon index $\Gamma \sim 1.5–2$ (Campana et al. 1998a, Tavani & Arons 1997).

**First summary.** Which emission models agree with the observational data of SXRTs in quiescence? Actually there are two main models, even if there is no consensus on them and are not particularly well defined. The first consideration is that the soft and the hard components seem not to come from the same emission mechanism. One class of models involve accretion onto the neutron star surface as the main ingredient. The model presented in Menou et al. (1999) involves an ADAF (responsible for the hard component) and a propeller (for the soft component). Other possibilities, even if never
investigated in details, involve direct accretion onto the neutron star surface (resulting in a soft spectrum, e.g. Zampieri et al. 1995) and a corona for the power law. The other family involves the cooling of the neutron star as responsible for the soft component. The hard component is explained as the interaction of the pulsar relativistic wind with matter outflowing from the companion (Campana et al. 1998a, Campana & Stella 2000).

**HOW CAN WE IMPROVE THE SITUATION?**

**Better X–ray spectra.** The first and easiest way is to obtain further X–ray observations. But this will not directly produce breakthroughs unless very peculiar sources, otherwise we will gain knowledge in the statistical properties of the sources. The main problem is that the ADAF models do not produce firm spectral predictions\(^2\).

**Radio pulsar search.** In the shock emission scenario an active radio pulsar is predicted. One can try to search for pulsed radio signals. These have been searched for in a sample of 5 SXRTs in quiescence with negative results (Burgay et al. 2003). This non-detection is significant since the probability of having missed all the observed sources because of their weakness or beaming is only about 25\%. However, as already noted (Campana et al. 1998a, Burderi et al. 2003), radio emission can be severely hampered by free-free absorption of matter around the system. High frequency searched would be very valuable.

**X–ray variability.** A different path consists in studying well known sources in much higher details than have been done since now. This is possible thanks to the new X–ray facilities like Chandra and XMM-Newton and this has been done on the two best studied SXRTs: Aql X-1 and Cen X-4.

- The first source has been monitored during quiescence with Chandra for 4 times over 5 mouths with particular care to the systematic effects: Aql X-1 has always been observed on the same position of the Chandra CCDs and with a sub-imaging in order to reduce any pile-up effect (Rutledge et al. 2002). This analysis showed that the temperature of the neutron star atmosphere varied as \(kT = 130^{+3}_{-5}\) eV, down to \(113^{+5}_{-4}\) eV, and finally increasing to \(118^{+9}_{-4}\) eV for the final two observations. A power law tail was detected only in the last two observations. Short term variability (32\%\% rms) was also observed in the last observation (when the power law tail contributes more). Given this variability in temperature the cooling neutron star model is not able to explain the data and (Rutledge et al. 2002) concluded that accretion onto the neutron star surface was more likely. Campana & Stella (2003) approached the same data plus an unpublished BeppoSAX observation of Aql X-1 on the same epoch. They obtained a good fit with a variable temperature model but a similarly good fit for a varying power law plus column density model. These correlated changes are expected based on the shock emission scenario in light of the recent observations of the ms pulsar PSR 1740–5340 showing variable emission along the orbit and with difference from orbit to orbit (D’Amico et

\(^2\) This is almost true for the shock emission scenario in which a synchrotron spectrum is expected but Compton losses may steepen the spectrum.
al. 2001). This testifies for a vary variable ambient around all these systems which can result in correlated changes between the matter along the line of sight and the energy emitted.

- Cen X-4 was observed by XMM-Newton during quiescence. Given the closeness of Cen X-4 (1.2 kpc) this provides the observation of a SXRT in quiescence with the highest signal to noise ratio. The quiescent state of Cen X-4 has been recognised to be variable both on long timescales (∼40% in 5 yr, Rutledge et al. 2001) and on shorter timescales (factor of ∼3 in a few days, Campana et al. 1997). During this XMM-Newton observation X-ray variability has been observed (at a level of 45 ± 7% rms in the 10^{-4} − 1 Hz range) thanks to the large collecting area. Variability on such a short timescale would have been missed if observed with any previous X-ray satellite (Campana et al. 2003). In the EPIC-pn instrument light curve three flare-like events can be identified. Flare activity has been recently reported also in the optical for a number of transient black holes during quiescence as well as for Cen X-4 (Zurita et al. 2003, Hynes et al. 2002). Flares occur on timescales of minutes to a few hours, with no dependence on orbital phase. The mean duration of optical flares in Cen X-4 is 21 min. This is similar to what observed in the X-rays.

Small spectral variations are observed as well. In order to highlight the cause of this variability, we divided the data into intensity intervals and fit the resulting spectra with the canonical model for neutron star transients in quiescence. The variability can be mainly accounted for by a variation in the column density together with another spectral parameter (either power law index or neutron star atmosphere temperature). Based on the available spectra we cannot prefer a variation of the power law versus a variation in the temperature of the atmosphere component (even if the first is slightly better in terms of reduced $\chi^2$, Campana et al. 2003). Variations in the neutron star atmosphere might suggest that accretion onto the neutron star surface is occurring in quiescence (e.g. Rutledge et al. 2002); variations in the power law tail should support the view of an active millisecond radio pulsar emitting X-rays at the shock between a radio pulsar wind and inflowing matter from the companion star (e.g. Campana & Stella 2003).

**SUMMARY**

SXRT sources are disclosing their secrets thanks to the new astronomical facilities. This is mainly occurring in the X-ray band, as expected, since they emit the bulk of their electromagnetic radiation in this band. XMM-Newton and Chandra are observing with unprecedented details these sources, finding unexpected results also for well known sources. Observations in other bands (mainly radio and optical) are providing valuable information too. Two models have been put forward to explain the main emission properties of SXRTs in quiescence: one involve accretion onto the neutron star (onto the surface or associated with an ADAF and a propeller) and the other an active radio pulsar the relativistic wind of which interacts with the mass outflowing from the companion. These emission mechanisms are not encompassed by persistent sources. The ADAF scenario involves a large mass inflow rate variation from outburst to quiescence (which is not observed in the parent population of TBHs, (Campana & Stella 2000) and a working
propeller or a strong outflow. The pulsar scenario does not involve any accretion onto the neutron star surface and the luminosity that we see comes from cooling of the neutron star (soft component) and interaction of the relativistic pulsar wind with matter (hard component).

REFERENCES

1. Brown, E. F., Bildsten, L., Rutledge, R. E. 1998, ApJ, 504, L95
2. Burderi, L., Di Salvo, T., D’Antona, F., Robba, N. R., Testa, V. 2003, A&A, 404, L43
3. Burgay, M., Burderi, L., Possenti, A., D’Amico, N., Manchester, R. N., Lyne, A. G., Camilo, F., Campana, S. 2003, ApJ, 589, 902
4. Campana, S. 2001, in “X–ray astronomy : stellar endpoints, AGN, and the diffuse X–ray background”, eds. N.E. White, G. Malaguti, G.G.C. Palumbo, AIP 599 63
5. Campana, S., Stella, L. 2000, ApJ, 541, 849
6. Campana, S., Stella, L. 2003, ApJ, in press (astro-ph/0307213)
7. Campana, S., Mereghetti, S., Stella, L., Colpi, M. 1997, A&A, 324, 941
8. Campana, S., Colpi, M., Mereghetti, S., Stella, L., Tavani, M. 1998a, A&A Rev., 8, 279
9. Campana, S., Stella, L., Mereghetti, S., Colpi, M., Tavani, M., Ricci, D., Dal Fiume, D., Belloni, T. 1998b, ApJ, 499, L65
10. Campana, S., Stella, L., Gastaldello, F., Mereghetti, S., Colpi, M., Israel, G. L., Burderi, L., Di Salvo, T., Robba, R. N. 2002, ApJ, 575, L15
11. Campana, S., Israel, G. L., Stella, L., Gastaldello, F., Mereghetti, S. 2004, ApJ in press (astro-ph/0309775)
12. Colpi, M., Geppert, U., Page, D., Possenti, A. 2001, ApJ, 548, L175
13. D’Amico, N., et al. 2001, ApJ, 561, L89
14. Fender, R. P., Gallo, E., Jonker, P. G. 2003, MNARS, 343, L99
15. Garcia, M. R., McClintock, J. E., Narayan, R., Callanan, P., Barret, D., Murray, S. S. 2001, ApJ, 553, L47
16. Hynes, R. I., Zurita, C., Haswell, C. A., Casares, J., Charles, P. A., Pavlenko, E. P., Shugarov, S. Yu., Lott, D. A. 2002, MNARS, 330, 1009
17. Illarionov, A. F., Sunyaev, R. A. 1975, A&A, 39, 185
18. Kong, A. K. H., McClintock, J. E., Garcia, M. R., Murray, S. S., Barret, D. 2002, ApJ, 570, 277
19. Menou, K., Esin, A. A., Narayan, R., Garcia, M. R., Lasota, J.-P., McClintock, J. E. 1999, ApJ, 520, 276
20. Menou, K., McClintock, J. E. 2001, ApJ, 557, 304
21. Pooley, D., et al. 2003, ApJ, 591, L131
22. Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., Zavlin, V. E. 2001, ApJ 551, 921
23. Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., Zavlin, V. E. 2002, ApJ, 577, 346
24. Tavani, M., Arons, J. 1997, ApJ, 477, 439
25. Yi, I., Narayan, R., Barret, D., McClintock, J. E. 1996, A&AS, 120, 187
26. Wijnands, R., Heinke, C. O., Pooley, D., Edmonds, P. D., Lewin, W. H. G., Grindlay, J. E., Jonker, P. G., Miller, J. M. 2003, ApJ submitted (astro-ph/0310144)
27. Wijnands, R., van der Klis, M. 1998, Nature, 394, 344
28. Zampieri, L., Turolla, R., Zane, S.,Treves, A. 1995, ApJ, 439, 849
29. Zurita, C., Casares, J., Shahbaz, T. 2003, ApJ, 582, 369