PROCEEDINGS OF SCIENCE

Low energy indicators of high energy processes in cosmic sources

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X-ray binaries are cauldrons of fundamental physical processes which appear along practically the whole electromagnetic spectrum. The sub-class of X-ray transient sources show multifrequency behaviour which deserve particular attention in order to understand the causing physics. These binary systems consist of a compact star and an optical star, therefore there is a mutual influence between these two stars that drive the low energy (LE) (i.e. radio, IR, optical) and high energy (HE) processes. The LE processes are produced mostly on the optical star and the HE processes mostly on the compact star, typically a neutron star. Thus it appears evident that through the study of LE processes it is possible to understand also the HE processes and vice versa. In this paper we will discuss this problem starting from the experimental evidence of a delay between LE and HE processes detected for the first time in the X-ray/Be system A0535+26/HDE245770 (e.g. Giovannelli & Sabau-Graziati, 2011; Giovannelli, Bisnovatyi-Kogan & Klepnev, 2013 (here after GBK13); Giovannelli et al., 2015). This delay is common in cataclysmic variables (CVs) and other binary systems with either a neutron star or a black hole.

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1. Introduction

In the Galaxy there are different kinds of compact sources: white dwarfs (WDs), neutron stars (NSs) and black holes (BHs), both isolated and in binary systems. Thousand of papers devoted to these cosmic sources are available in literature. We mention the last available exhaustive review by Postnov & Yungelson (2014) about "*The Evolution of Compact Binary Stars Systems* in which they review the formation and evolution of compact binary stars consisting of WDs, NSs, and BHs. Merging of compact-star binaries are expected to be the most important sources for forthcoming gravitational-wave (GW) astronomy.

Several review papers have been published for discussing the different classes of galactic compact sources: i) Cataclysmic Variables (CVs) and related objects (e.g. Giovannelli, 2008; Giovannelli & Sabau-Graziati, 2012; 2015); ii) High Mass X-ray Binaries (HMXBs) (e.g. Giovannelli & Sabau-Graziati, 2001, 2004, and van den Heuvel, 2009 and references therein; iii) Obscured Sources and Supergiant Fast X-Ray Transients (e.g. Chaty, 2011); iv) Ultra–Compact Double–Degenerated Binaries (e.g. Wu, Ramsay & Willes, 2008; Wu, 2009); Magnetars (Kitamoto et al., 2014: White Paper for ASTRO-H Space X-ray observatory).

A summary of these topics can be found in the review paper by Giovannelli & Sabau-Graziati (2014).

In the following we will discuss the X-ray/Be system A 0535+26/HDE 245770 that triggered the work related to the explanation of the problem of the time–delay between the X-ray and optical flashes experimentally encountered when the neutron star approaches the periastron.

2. The X-ray/Be system A 0535+26/HDE 245770

The X-ray source A 0535+26 was discovered by the Ariel V satellite on April 14, 1975 (Coe et al., 1975). The X-ray source was in outburst with intensity of ~ 2 Crab and showed a pulsation of ~ 104 s (Rosenberg et al., 1975). The hard X-ray spectrum during the decay from the April 1975 outburst became softer, so that the 19 May spectrum had $E^{-0.8}$ and the 1 June spectrum $E^{-1.1}$ (Ricketts et al., 1975). Between 13 and 19 April, 1975, as the nova brightened, the spectra showed some evidence of steepening. The best fit of the experimental data between roughly 27 and 28 April was compatible with an 8 keV black-body curve (Coe et al., 1975). The X-ray source decayed from the outburst with an *e*-folding time of 19 days in the energy range of 3-6 keV (Kaluzienski et al., 1975). The Be star HDE 245770 – later nicknamed Flavia' star (Giovannelli & Sabau-Graziati, 1992) – was discovered as the optical counterpart of A 0535+26 by Bartolini et al. (1978), and was classified as an O9.7IIIe star by Giangrande et al. (1980).

Complete reviews of this system can be found in Giovannelli et al. (1985), Giovannelli & Sabau-Graziati (1992), and Burger et al. (1996).

Briefly, the properties of this system, placed at a distance of 1.8 ± 0.6 kpc (Giangrande et al., 1980), can be summarized as follows: a hard X-ray transient, long-period X-ray pulsar – the secondary star – is orbiting around the primary O9.7IIIe star. The masses are of $\sim 1.5 \pm 0.3$ $M_\odot$ (Joss & Rappaport 1984; Thorsett et al. 1993; van Kerkwijk, van Paradijs, J. & Zuiderwijk, 1995), and 15 $M_\odot$ (Giangrande et al., 1980) for the secondary and primary star, respectively. The eccentricity is e = 0.47 (Finger et al., 1994). Usually the primary star does not fill its Roche lobe (de Loore et al., 1984). However, the suggestion that there might be a temporary accretion disk around the X-ray pulsar when it approaches periastron (Giovannelli & Ziółkowski, 1990) was confirmed by the X-ray measurements of Finger, Wilson & Harmon (1996) and was discussed by Giovannelli et al. (2007).

The first suggestion of Bartolini et al. (1983) about the value of the orbital period ($P_{orb} = 110.856 \pm 0.002$ days), allowed Giovannelli & Sabau-Graziati (2011) to discover a systematic delay ($\sim$ 8 days) of the X-ray outbursts with respect to the periastrons passages of the neutron star. Just a little before or simultaneously to the periastron, the system experiences an optical brightening ranging from ≈ 0.02 to ≈ 0.2 magnitudes.

The trigger of this discovery was the optical flare occurred at JD 2,444,944 (5th December 1981) (hereafter 811205-E; E stands for event) (Giovannelli et al., 1985) and followed by a short X-ray outburst (811213-E) (Nagase et al., 1982) – predicted by a private communication of Adriano Guarnieri (member of Giovannelli's group) to the team of Hakucho Japanise X-ray satellite. Unfortunately in the following years simultaneous optical an X-ray measurements were not always obtained around periastron passage. However, the available data were sufficient for showing the aforementioned systematic delay.

In order to explain and describe the 8-day delay between periastron passage and X-ray outbursts, GBK13 constructed a model adopting the orbital period determined by Priedhorsky & Terrell (1983) from X-ray data ($P_{orb} = 111.0 \pm 0.4$ days), and the ephemeris $JD_{opt-outb} = JD_0$(2,444,944) $\pm$ n(111.0 $\pm$ 0.4) days; the 111-day orbital period agrees within the error bars with many other determinations reported in the literature (from optical data, e.g. Guarnieri et al., 1985; de Martino et al., 1985; Hutchings, 1984; Janot-Pacheco, Motch & Mouchet, 1987. From X-ray data, e.g. Nagase et al., 1982; Priedhorsky & Terrell, 1983; Motch et al., 1991; Finger, Wilson & Harmon, 1996; Coe et al., 2006; Finger et al., 2006).

In the following we will discuss the experimental results that corroborate GBK13 model, by the analysis of several results coming from multifrequency LE and HE observations of A 0535+26/HDE 245770 nicknamed Flavia' star.

3. Time delay between optical and X-ray outbursts in A 0535+26/HDE 245770

A description of the time–delay among many optical and X-ray events occurring around the periastron passages in the system A 0535+26/HDE 245770 have been presented in the papers by GBK13 and Giovannelli et al. (2015). However, just to remark the importance of the experimental evidence of such a time–delay we will present a few more examples that in our opinion definitively support the validity of the model developed in GBK13. Briefly, the model is the following: in the vicinity of periastron the mass flux $\dot{M}$ increases (depending on the activity of the Be star) between $\approx 10^{-8}$ and $\approx 10^{-7}$ $M_{\odot}$ yr^{-1}. The outer part of the accretion disk – geometrically thin and optically thick without advection (Shakura & Sunyaev, 1973; Bisnovatyi-Kogan, 2002) – becomes hotter, therefore the optical luminosity (L_{opt}) increases. Due to large turbulent viscosity, the wave of the large mass flux is propagating toward the neutron star, thus the X-ray luminosity (L_x) increases due to the appearance of a hot accretion disk region and due the accretion flow channeled by the magnetic field lines onto magnetic poles of the neutron star. The time–delay τ is the time between the optical and X-ray flashes appearance. Figure 1 shows a sketch of this model.

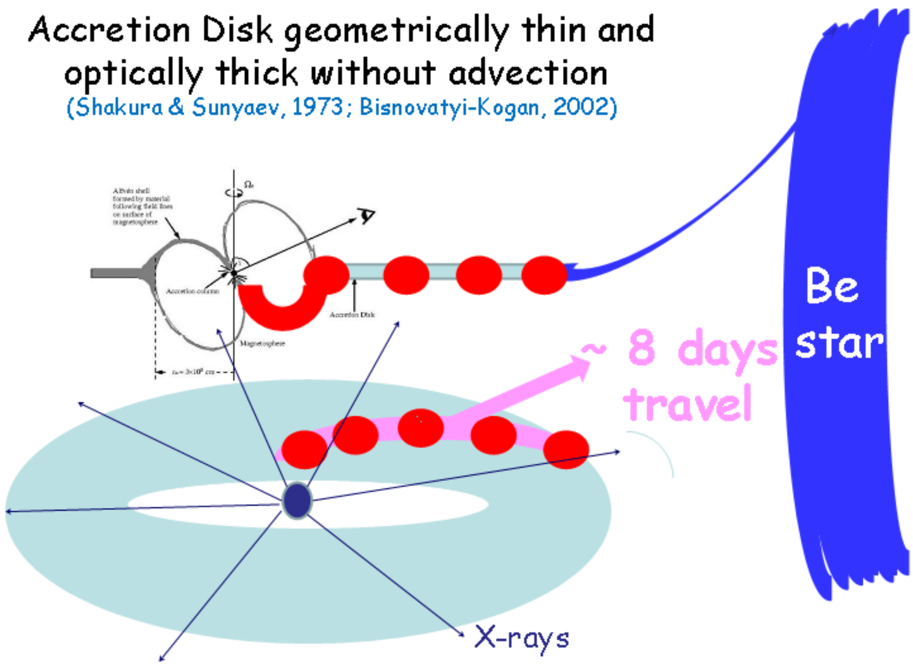

Figure 1: Sketch of the viscous accretion disk model for explaining the time-delay between X-ray and optical flashes.

By using the ephemerides given by GBK13, namely:

$JD_{opt-outb} = JD_0(2,444,944) \pm n(111.0 \pm 0.4)$ days

that fixed the reference point at the date 5th December 1981 (811205-E), it was possible to explain the behaviour of the system during the year 2014 (Giovannelli et al., 2015). It was possible not only to predict the arrival time of the X-ray outbursts following the optical flashes, but also the intensity I_x of the X-ray flares, thanks to the relationship I_x versus ΔV_{mag}, where ΔV_{mag} is the relative variations of the V magnitude of the Be star around the periastron passage with respect to the level before and after such a passage. This relationship is shown in Fig. 2 (adapted from Giovannelli et al., 2015).

We have also found a relationship between the equivalent width (EW) of H_α and I_x. The values of H_α-EW have been taken only if measurements were performed around the periastron passage ± 10 days. Unfortunately few measurements have been found in this time range. However, the trend of the relationship is rather good, as shown in Fig. 3, where data taken from Camero-Arranz et al. (2012), Yan, Li & Liu (2012), Giovannelli et al. (2016) are reported (Fasano, 2015). It is interesting to note that in one occasion, at the 106th periastron passage (JD 2,456,710 = 21 Feb 2014) after 811205-E, optical photometry and spectroscopy as well as X-ray measurements from different experiments were obtained. A jump in the H_α-EW and H_β-EW in correspondence with the rise of X-ray intensity was detected, being the jump of H_β-EW delayed of ≈ 5 days with respect to that of H_α-EW. This important result deserves further investigations. However, the jumps of H_α-EW and H_β-EW could originate because of a contribution to the total emission in those lines coming from the temporary accretion disk around the neutron star (Giovannelli et al., 2015, and the references therein). And if so, the delay between H_β-EW and H_α-EW jumps should be explicable

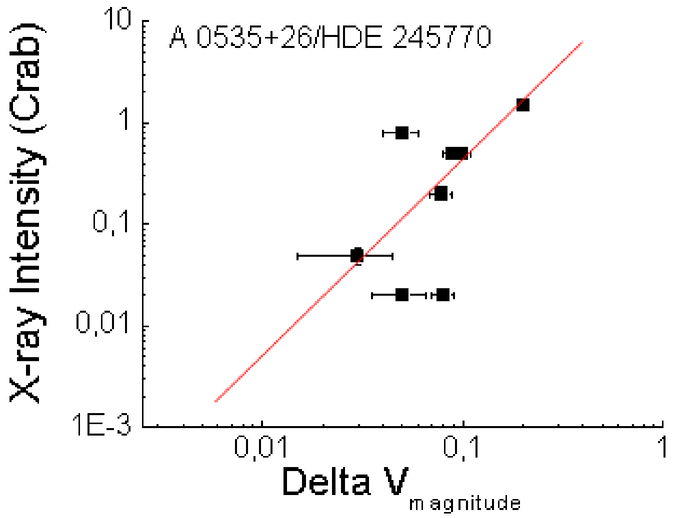

Figure 2: Intensity of the X-ray flare of A 0535+26 versus the variation of V magnitude of HDE 245770 around the periastron passage (adapted from Giovannelli et al., 2015).

within the framework of GBK13's model.

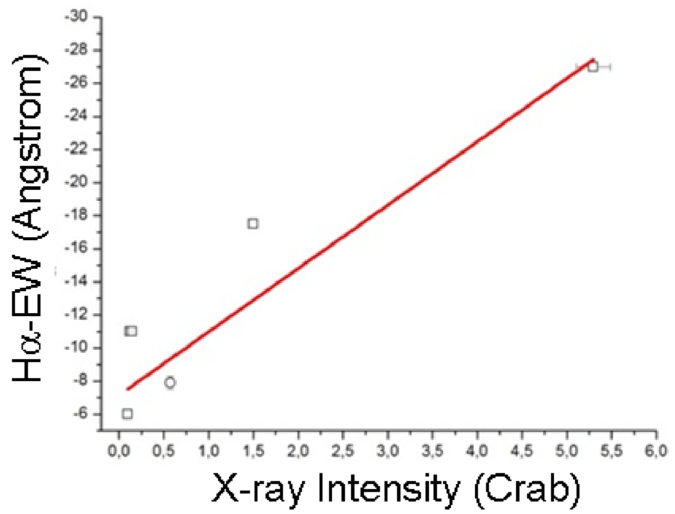

Figure 3: Intensity of the X-ray flare of A 0535+26 versus the equivalent width of H_α of HDE 245770 around the periastron passage (data taken from Camero-Arranz et al., 2012; Yan, Li & Liu, 2012; Giovannelli et al., 2016) (figure adopted from Fasano, 2015).

An impressive strong optical event have been detected on March 19, 2010 (JD 2,455,275). On the basis of such a strong optical activity – especially H_γ in emission – Giovannelli, Gualandi & Sabau-Graziati (2010, ATel 2497) predicted the incoming X-ray outburst of A 0535+26, which actually occurred (Caballero et al., 2010b, ATel 2541). The X-ray intensity reached was 1.18 Crab on April 3, 2010 in the range 15–50 keV of BAT/SWIFT (Caballero et al., 2010a,b,c,d; Caballero et al., 2011). Figure 4 shows the March–April 2010 event. The X-ray flare started about 8 days after the 93th periastron passage after the 811205-E, just when optical spectroscopy was performed by Giovannelli, Gualandi & Sabau-Graziati (2010), and reached the maximum about 12 days later and decayed in about 20 days roughly as occurred in 1975 when A0535+26 was discovered by the Ariel V satellite.

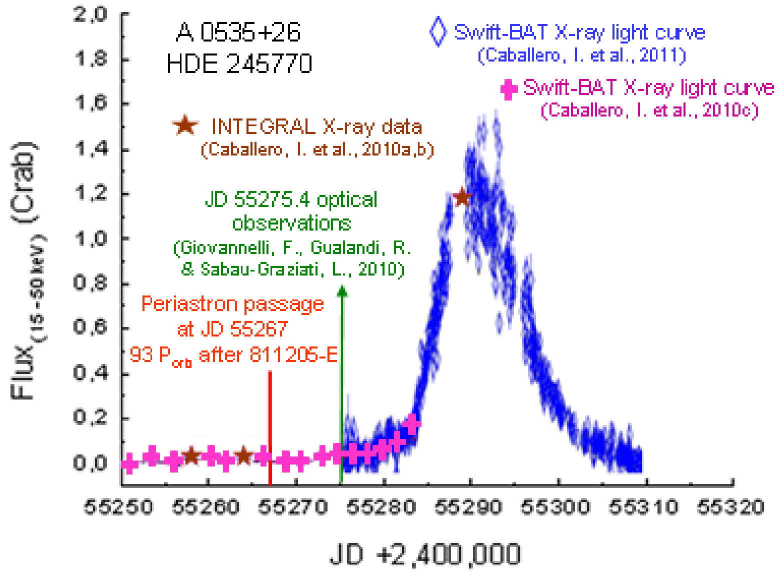

Figure 4: The predicted March–April 2010 X-ray outburst of A 0535+26 (Giovannelli, Gualandi & Sabau-Graziati, 2010) after the 93th passage at the periastron after 811205-E (Caballero et al., 2010a,b,c,d; Caballero et al., 2011).

Figure 5 shows the X-ray flux intensity of A 0535+26 as deduced by different measurements available in the late 1970'ies with obvious meaning of the symbols used (Giovannelli, 2005; Giovannelli & Sabau-Graziati, 2011). FG's intuition led him to investigate the rise of the X-ray flux (red line) at the 24th May 1977 measurement (red asterisk): he assumed that the evident rise of the X-ray flux would have produced an outburst similar to the first one occurred in 1975. Then with a simple extrapolation he predicted the fourth outburst, similar to the second: and this happened!

For this reason Giovannelli's group was observing in optical HDE 245770 around the predicted period for the 4th X-ray outburst of A 0535+26. The optical photometric measurements performed during 10–15 December 1977 allowed to Bartolini et al. (1978) to firmly demonstrate the association of HDE 245770 with the A 0535+26.

The astonishing fact that definitively demonstrate the goodness of GBK13's ephemerides and the mechanism triggering the X-ray outburst with a time–delay with respect to the optical flare around the periastron passage is reported in Fig. 6.

Indeed, in Fig. 6 the measurements of the first detection of A 0535+26 by Ariel V satellite are reported. Unfortunately in 1975, around the time of the discovery of A 0535+26 no optical measurements are available for obvious reasons. The vertical red line indicates the time of the periastron passage following GBK13's ephemeris. This passage occurred at the 22nd cycle before the 811205-E. The vertical blue line indicates the day April 7, 1975 (JD 2,442,510.4) just 115 cycles before the strong optical spectroscopic activity detected on March 19, 2010 (JD 2,455,275.4), that preceded the strong X-ray outburst reported in Fig. 4.

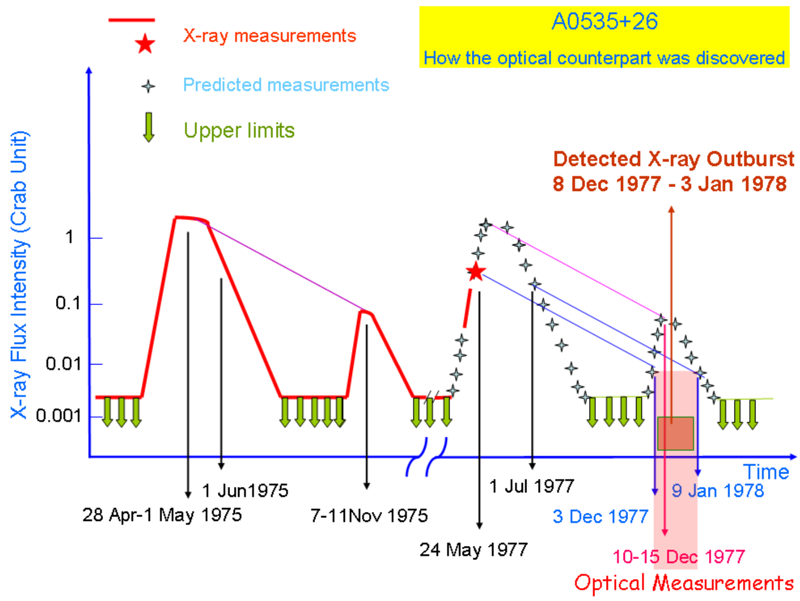

Figure 5: X-ray flux versus time of A 0535+26. X-ray measurements are reported with red lines and asterisk, upper limits with green arrows, and predicted fluxes with light blue stars. Periods of real detected X-ray outburst and optical measurements are marked too (Giovannelli, 2005; Giovannelli & Sabau-Graziati, 2011).

The similarity between the first X-ray outburst and that of March–April 2010 is evident, and the separation of the two events is exactly 115 cycles.

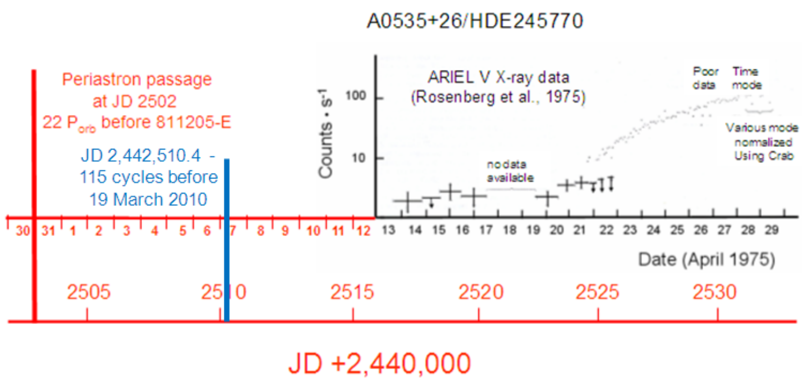

Figure 6: The Periastron passage at the 22nd cycle before 811205-E (JD 2502) (red line) precedes of $\sim$ 14 days the X-ray outburst of A 0535+26 which starts approximatively on JD 2516 (after Rosenberg et al., 1975). The vertical blue line indicates the day April 7, 1975 (JD 2,442,510.4) just 115 cycles before the strong optical spectroscopic activity detected on March 19, 2010 (JD 2,455,275.4) (after GBK13).

4. Conclusions

It is right to remind that the mechanism proposed by GBK13 for explaining the X-ray-optical delay in A 0535+26/HDE 245770 is based on an enhanced mass flux propagation through the viscous accretion disk. This mechanism, known as UV-optical delay (the delay of the EUV flash with respect to the optical flash) was observed and modelled for cataclysmic variables (e.g. Smak, 1984; Lasota, 2001). Time delays have been detected also in several other X-ray transient binaries. This is the reason that urged Bisnovatyi-Kogan & Giovannelli (2016) to generalize the aforementioned model, developed for the particular case of A 0535+26/HDE 245770. This general model provides the formula (4.1) of the time delay in transient cosmic accreting sources:

$$\tau = 6.9 \frac{\mathrm{m}^{2/3}\dot{\mathrm{m}}^{1/15}}{\alpha^{4/5}\,(\mathrm{T}_4)^{28/15}} \tag{4.1}$$

where:
$\mathrm{m} = \mathrm{M}/\mathrm{M}_{\odot}$; $\dot{\mathrm{m}} = \dot{\mathrm{M}}/(10^{-8}\ \mathrm{M}_{\odot}/\mathrm{yr})$; $\mathrm{T}_4 = \mathrm{T}_0/10^4$ K ; α = viscosity , and
T_0 = maximum temperature in optics.

By using this formula it is possible to obtain an excellent agreement between the experimental and theoretical delays found in:

- X-ray/Be system A0535+26/HDE245770: $\tau_{exp} \simeq 8$ days (GBK13); $\tau_{th} \simeq 8$ days;
- Cataclysmic variable SS Cygni; τ_{exp} = 0.9–1.4 days (Wheatley, Mauche & Mattei, 2003); $\tau_{th} \simeq 1.35$ days;
- Low-mass X-ray binary Aql X-1/V1333 Aql: $\tau_{exp} \sim 3$ days (Shahbaz et al., 1998); $\tau_{th} \simeq$ 3.2days
- Black hole X-ray transient GRO J1655-40: $\tau_{exp} \sim 6$ days (Orosz et al., 1997); $\tau_{th} \simeq 6.5$ days.

In order to better clarify the behaviour of X-ray transient sources it is mandatory to follow such sources along the whole orbital period with simultaneous multifrequency observations with particular emphasis to optical photometry and spectroscopy and to X-ray measurements in different energy regions.

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