

Observations of short-duration X-ray transients by WATCH on Granat

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Abstract. During 1990–92, the WATCH all-sky X-ray monitor on *Granat* discovered six short-duration X-ray transients. In this paper we discuss their possible relationship to peculiar stars. Only one of the fast (few hours) X-ray transients (GRS 1100–771) might be tentatively ascribed to a superflare arising from a young stellar object in the Chamaeleon I star-forming cloud. At the distance of ~ 150 pc, $L_x = 1.35 \times 10^{34}$ erg s⁻¹ (8–15 keV), or 2.6×10^{34} erg s⁻¹ (0.1–2.4 keV) assuming a thermal spectrum with $kT \sim 10$ keV, a temperature higher than those previously seen in T Tauri stars (Tsuboi et al. 1998). The peak X-ray luminosity is at least 2 times higher than that derived for the protostar IRS 43 (Grosso et al. 1997) which would make –to our knowledge– the strongest flare ever seen in a YSO. However, the possibility of GRS 1100–771 being an isolated neutron star unrelated to the cloud cannot be excluded, given the relatively large error box provided by WATCH. Regarding the longer duration (~ 1 day) X-ray transients, none of them seem to be related to known objects. We suggest that the latter are likely to have originated from compact objects in low-mass or high-mass X-ray binaries, similarly to XTE J0421+560.

Key words: stars: flare – stars: pre-main sequence – ISM: individual objects: Chamaeleon I cloud – X-rays: bursts – X-rays: stars

1. Introduction

Amongst the many kinds of sources in the variable X-ray sky, X-ray transients have been observed since the first experiments in the late 60's. According to their duration, it is possible to distinguish between Long-duration X-ray Transients (lasting from weeks to few months) and Short-duration X-ray Transients (lasting from hours to very few days).

Long-duration X-ray Transients are mainly related to Be-neutron star systems (Be X-ray Transients) and to Soft X-ray Transients (a subclass of low-mass X-ray binaries). The latter

include the best black hole candidates found so far (Tanaka & Shibazaki 1996).

But not too much is known with respect to most of Short-duration X-ray Transients. The main reason is the lack of counterparts at other wavelengths. One subclass are the so-called Fast X-ray Transients, that have been observed with many detectors since the launching of the *Vela* satellites (Heise et al. 1975, Cooke 1976) until the advent of the *BeppoSAX* satellite (Heise et al. 1998). Durations range from seconds (Belian, Conner & Evans 1976) to less than few hours. Normally, they have been seen once, and never seen in quiescence, implying high peak-to-quiescent flux ratios (10^2 – 10^3) (Ambruster et al. 1983). Spectral characteristics vary substantially, from a hard spectrum in MX 2346–65 ($kT \sim 20$ keV; Rappaport et al. 1976) to soft spectra with blackbody temperatures from $kT = 0.87$ to 2.3 keV (Swank et al. 1977). In two cases, precursors to the main event were observed by *SAS 3* (Hoffman et al. 1978). The precursors rose and fell in brightness in less than 0.4 s. In the Ariel V database, 27 sources were discovered (Pye & McHardy 1983), and 10 more were detected in the *HEAO 1* A-1 all sky survey (Ambruster & Wood, 1986), implying a fast transient all-sky event rate of 1500 yr^{-1} for fluxes $F_x \geq 3 \times 10^{-10}$ erg cm⁻² s⁻¹ in the 2–10 keV energy band. In the *HEAO 1* A-2 survey, 52 events were found (Connors 1988), but 37 of them were related to four of the brightest X-ray sources in the LMC.

Due to the large difference of observational characteristics, it seems that these events are caused by more than one physical mechanism. In several cases, there have been tentative optical identifications on the basis of known sources in the transient error boxes. One suggestion has been that many of the fast X-ray transients are related with stellar flares originated in active coronal sources, like RS CVn binaries or dMe-dKe flare stars. RS CVn systems are binaries formed by a cool giant/subgiant (like a K0 IV) with an active corona and a less massive companion (a late G-dwarf) in a close synchronous orbit, with typical periods of 1–14 d. Peak luminosities are usually $L_x \sim 10^{32}$ erg s⁻¹. The RS CVn system LDS 131 was identified with the X-ray transient detected by *HEAO 1* on 9 Feb 1977 (Kaluzienski et al. 1978). The highest peak luminosity was recorded by *Ariel*

V for the flare observed from DM UMa in 1975 (Pye & McHardy, 1983). The hardest flare yet observed was for the system HR 1099, on 17 Feb 1980, which was detected by *HEAO 2* at energies up to 20 keV (Agrawal & Vaidya 1988). The most energetic X-ray flare was observed by *GINGA* from UX Ari. Its decay time was quite long (~ 0.5 days).

X-ray flares can be also observed from M or K dwarfs with Balmer lines in emission (these are the active cool dwarf stars dMe-dKe). In the *Ariel V* sky survey, Rao & Vahia (1984) suggested seven dMe stars as responsible of X-ray flares that reached peak luminosities $L_x \leq 10^{32}$ erg s $^{-1}$

(2–18 keV). AT Mic is the dMe star with the largest number of recorded events (four), with a big flare in 1977 (Kahn et al. 1979) reaching a peak luminosity $L_x = 1.6 \times 10^{31}$ erg s $^{-1}$ (2–18 keV), which is ~ 100 times larger than the strongest solar flares. One of the most energetic flares was the flare observed by *EXOSAT* in YY Gem on 15 Nov 1984. Pallavicini et al. (1990) estimated a total energy flare $E_x = 10^{34}$ erg (0.005–2 keV), and a decay time $t_d = 65$ min (one of the longest decay times ever measured for such events). One of the longest flare ever reported was observed for more than 2 hours for the X-ray source EXO 040830-7134.7 (van der Woerd et al. 1989).

X-ray flares have been observed from Algol-type binaries (Schnopper et al. 1976, Favata 1998), W UMa systems and young stellar objects (YSOs). Most of the YSOs are deeply embedded young stars and T Tauri stars. T Tauri stars are pre-main sequence stars (ages 10^5 – 10^7 yr) that may exhibit X-ray flaring activity via thermal bremsstrahlung from a hot plasma (see Linsky 1991). Montmerle et al. (1983) reported a “superflare” in the T Tauri star ROX-20, in the ρ Oph Cloud Complex, which reached a peak luminosity $L_x = 1.1 \times 10^{32}$ erg s $^{-1}$ (0.3–2.5 keV), and an integrated flare X-ray energy $E = 10^{34}$ erg. An *ASCA* observation of a flare in V773 Tau implied $L_x \sim 10^{33}$ erg s $^{-1}$ (0.7–10 keV), and a total energy release of $\sim 10^{37}$ erg, which is among the highest X-ray luminosities observed for T Tau stars (Tsuboi et al. 1998). Recently, X-ray activity in protostars has been detected. These are objects closely related to T Tau stars, with ages 10^4 – 10^6 yr, which are known to be strong X-ray sources when they enter the T Tauri phase. See Montmerle et al. (1986) and Montmerle & Casanova (1996) for comprehensive reviews. Koyama et al. (1996) reported an extremely high temperature (kT ~ 7 keV) *quiescent* X-ray emission from a cluster of protostars detected by *ASCA* in the R CrA molecular cloud. Preibisch (1998) also reported a *ROSAT* observation of the source EC 95 within the Serpens star forming region, for which a *quiescent* (dereddened) soft X-ray luminosity of $\sim (6\text{--}18) \times 10^{32}$ erg s $^{-1}$ is derived, which is at least 60 times larger than that observed for other 7 YSOs. Two of these YSOs have displayed flaring activity. In particular, IRS 43 in the ρ Oph cloud showed an extremely energetic superflare with a *peak* luminosity of $L_x = 6 \times 10^{33}$ erg s $^{-1}$ (0.1–2.4 keV) (Grosso et al. 1997).

Theoreticians have suggested other sources like dwarf novae (Stern, Agrawal & Riegler 1981) or bizarre type I X-ray bursts (Lewin & Joss 1981) as origin of some fast X-ray transients.

2. Observations

The WATCH instrument is the all-sky X-ray monitor onboard the *Granat* satellite, launched on 1 Dec 1989. It is based on the rotation modulation collimator principle (Lund 1985). The two energy ranges are approximately 8–15 and 15–100 keV. Usually, the uncertainty for the location of a new and short-duration source is 1° error radius ($3\text{-}\sigma$). More details can be found in Castro-Tirado (1994) and Brandt (1994).

2.1. Fast X-ray transients discovered by WATCH

During 1990–1992, WATCH discovered three bright fast X-ray transients. A small quantity when we compare with the other instruments mentioned above. This is mainly due to the higher low energy cut-off for WATCH (~ 8 keV), implying that only the harder events are detected. The events were immediately noticeable as an increase in the low energy count rate (Fig. 1) lasting up to a few hours. No positive detections were made for the higher energy band. Their observational characteristics are summarized on Table 1.

2.2. Longer duration X-ray transients discovered by WATCH

Three objects were also discovered by WATCH during 1990–92, although it is likely that some others are present in the whole WATCH data base (1990–96). The sources reported here were observed to peak at X-ray fluxes up to 3×10^{-9} erg cm $^{-2}$ s $^{-1}$ in the 8–15 keV band, and were discovered by analysis of the corresponding modulation pattern data. Their observational characteristics are summarized on Table 2. A fourth event, *GRS 1133+54*, lasting for ~ 1 day on 19–20 Nov 1992 was reported by Lapshov et al. (1992).

2.3. Search for correlated X-ray flares

We have searched for X-ray flares in the WATCH data base that could have occurred in simultaneity to observed flares at other wavelengths reported elsewhere. The results were negative both for λ Eridani (a flare was observed by *ROSAT* on 21 Feb 1991, Smith et al. 1993) and AU Mic (a flare was observed by *EUVE* on 15 July 1992, Cully et al. 1993). In the case of EV Lac, no WATCH data were available for an extraordinary optical flare that occurred on 15 Sep 1991 (Gershberg 1992).

3. Discussion

3.1. The fast X-ray transients

The three events quoted on Table 1 imply a rate of ~ 5 year $^{-1}$. If the sources of the three events are galactic, their high latitude would suggest that they are close to us, although no nearby known flare stars (Pettersen 1991) have been found in the corresponding WATCH error boxes.

GRS 1100-771. Only four variable stars are catalogued in the WATCH error box: CS Cha, CT Cha, CR Cha and TW Cha. All are Orion-type variables. TW Cha undergoes rapid light changes

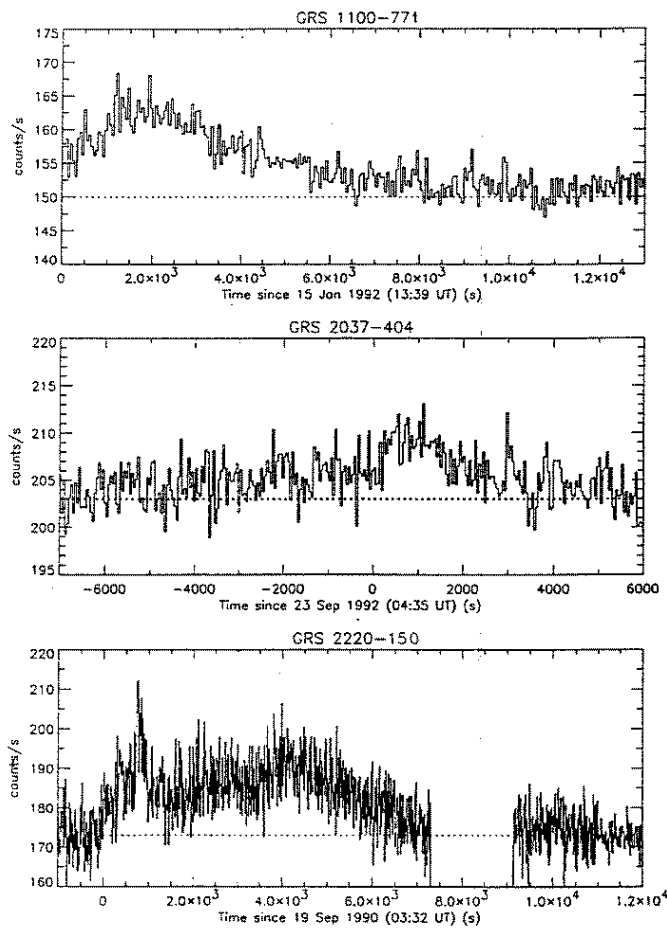
Table 1. WATCH fast X-ray transients.

Source	date	U.T. (onset)	duration (min)	$\alpha(2000.0)$	$\delta(2000.0)$	b	$F_{(8-15\text{ keV})}(\text{erg cm}^{-2}\text{ s}^{-1})$
GRS 1100-771	15 Jan 1992	13:39	90	11h 01m.2	-77°.4	-16°.0	5.0×10^{-9}
GRS 2037-404	23 Sep 1992	04:35	110	20h 41m.2	-39°.6	-38°.0	4.7×10^{-9}
GRS 2220-150	19 Sep 1990	03:32	240	22h 23m.1	-14°.6	-54°.0	1.3×10^{-8}

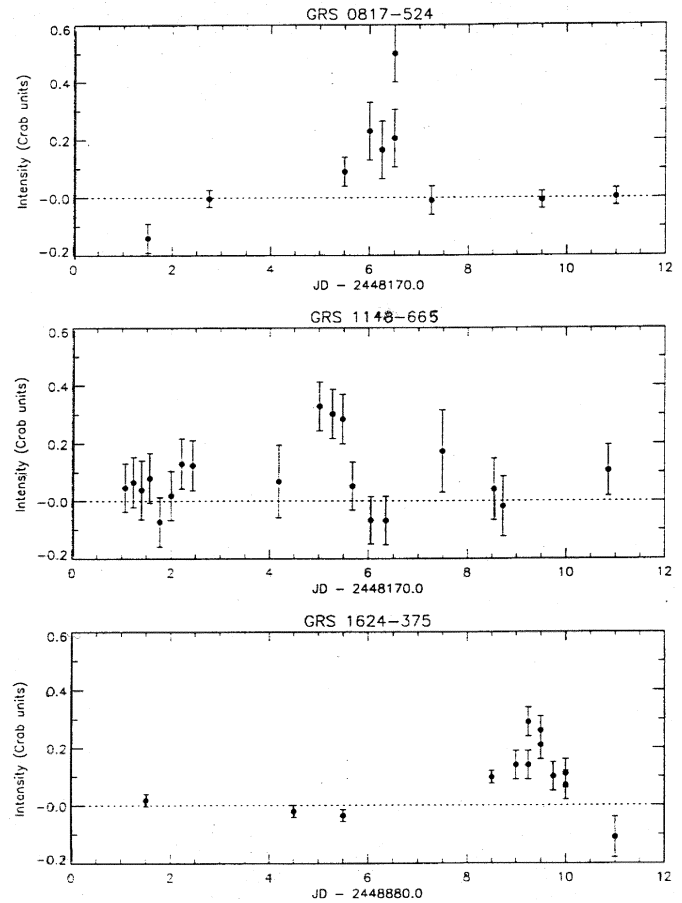
Table 2. WATCH long-lived X-ray transients.

Source	date	U.T. (onset)	duration (days)	$\alpha(2000.0)$	$\delta(2000.0)$	b	$F_{(8-15\text{ keV})}(\text{erg cm}^{-2}\text{ s}^{-1})$
GRS 0817-524	10 Oct 1990	14:00	~ 1	08h 19m.4	-52°.2	-8°.9	3.1×10^{-9}
GRS 1133+540 ^a	19 Nov 1992	12:00	~ 1	11h 35m.7	+53°.7	+60°.4	2.2×10^{-9}
GRS 1148-665	10 Oct 1990	12:00	~ 1	11h 50m.4	-66°.8	-4°.8	3.1×10^{-9}
GRS 1624-375	24 Sep 1992	03:00	~ 1	16h 27m.7	-37°.6	+7°.2	2.2×10^{-9}

^a Lapshov et al. 1992

**Fig. 1.** The X-ray light-curves in the 8–15 keV of the three fast X-ray transients discovered by WATCH on Granat.

with typical amplitudes of 1^m . The whole error box lies in the Chamaeleon I star-forming cloud, and the position of 41 (out of ~ 75) soft X-ray sources detected by *ROSAT* in the cloud (Alcalá et al. 1995), are compatible with the position for GRS 1100-771 derived from the WATCH data. The DENIS near-IR survey of the region has revealed 170 objects in the cloud, mostly

**Fig. 2.** The X-ray light-curves in the 8–15 keV of the three X-ray transients (lasting ~ 1 day) discovered by WATCH on Granat and discussed in this paper.

T Tau stars (Cambrésy et al. 1998). Feigelson et al. (1993) also found that $\sim 80\%$ of the X-ray sources are identified with T Tau stars with X-ray luminosities ranging from 6×10^{28} to 2×10^{31} erg s $^{-1}$.

The WATCH detection implies a *flaring* luminosity $L_x = 0.6 \times 10^{30} (\text{d}/1 \text{ pc})^2 \text{ erg s}^{-1}$ (8–15 keV), or $L_x = 1.2 \times 10^{30}$

$(d/1\text{ pc})^2 \text{ erg s}^{-1}$ (0.1–2.4 keV) for a thermal spectrum with $kT = 10\text{ keV}$ and no absorption (Greiner 1999). If the X-ray source lies in the Chamaeleon I cloud (at $\sim 150\text{ pc}$), $L_x = 1.35 \times 10^{34} \text{ erg s}^{-1}$ (8–15 keV), or $L_x = 2.6 \times 10^{34} \text{ erg s}^{-1}$ (0.1–2.4 keV), with an integrated flare energy of $\sim 10^{38} \text{ erg}$ across the X-ray band (0.1–10 keV). Taking into account that $kT \sim 10\text{ keV}$, a value higher than that observed in the T Tau star V773 (Tsuboi et al. 1998), and that the energy release would be ~ 100 times larger than that seen in the YSO IRS 15 in the ρ Oph cloud (Grosso et al. 1997), we tentatively suggest a superflare arising from one of the YSOs in the Chamaeleon I star-forming cloud as the most likely candidate for GRS 1100-771. If this is indeed the case, it will be difficult to explain how this exceptionally high X-ray luminosity can be explained by a solar-like coronal emission mechanism. However, a large amount of energy, stored in large magnetic structures that it is set free by magnetic reconnection events (see Grosso et al. 1997), can account for the WATCH detection. But we notice that the highest quiescent luminosity for any of the X-ray sources detected by *ROSAT* in the WATCH error box is $L_x \sim 10^{31} \text{ erg s}^{-1}$ (0.1–2.4 keV) at the utmost (Alcalá et al. 1997), i.e. 100 times lower than that seen in IRS 43 for which a steady supply of energy (like a large number of reconnection events) was proposed (Preibisch 1998). In any case, the possibility of GRS 1100-771 being an isolated neutron star unrelated to the cloud cannot be excluded, given the relatively large error box provided by WATCH.

GRS 2037-404. It was discovered on 23 Sep 1992 (Castro-Tirado, Brandt & Lund 1992), and lasted for 110 min, reaching a peak intensity of ~ 0.8 Crab. On our request, a Schmidt plate was taken at La Silla on 29 Sep, and based on this plate, it was reported the presence of the Mira star U Mic near maximum brightness at 7.0 mag (Della Valle & Pasquini, 1992). U Mic is a Mira star and we do not consider this star as a candidate due to the different timescales of the involved physical processes. Moreover it is too far away from the error box centre ($\sim 2^\circ$). Hudec (1992) proposed another variable object inside the WATCH error box as a candidate to be further investigated. This is the star RV Mic (B ~ 10.5) discovered in 1948 (Hoffmeister 1963). Although is classified as a Mira Cet type star, it is apparently a highly variable object. Another four variables are within the 1° radius WATCH error box: UU Mic (a RR Lyr type), UW Mic (a semi-regular pulsating star), SZ Mic (an eclipsing binary) and UZ Mic (an eclipsing binary of W UMa type). In any case, we carefully examined the Schmidt plate and found no object inside the 1° radius WATCH error box that would have varied by more than 0.5^m when comparing with the corresponding ESO Sky Survey plate.

GRS 2220-150. No variable stars are catalogued within the WATCH error box. The high flux (2.1 Crab) is similar to the peak of the fast transient at 20h14m +30.9 discovered by *OSO-8* in 1977 (Selermitsos, Burner & Swank 1979). The peak luminosity for GRS 2220-150 was $L_x = 1.5 \times 10^{30} (d/1\text{ pc})^2 \text{ erg s}^{-1}$ (8–15 keV), or $L_x = 6 \times 10^{30} (d/1\text{ pc})^2 \text{ erg s}^{-1}$ (2–15 keV) if we assume a Crab-like spectrum.

Considering the high peak luminosities, a flare of a dMe or a dKe star may be excluded in these two latter cases. No nearby RS CVn stars from the list of Lang (1992) were found in the error boxes. It can be possible that these events would be associated to old isolated neutron stars accreting interstellar matter with unstable nuclear burning (Ergma & Tutukov 1980). According to Zdukic et al. (1992), when the accretion rate is higher than 10^{13} g s^{-1} , the hydrogen burning triggered by electron capture becomes unstable. As the mass of the accreted envelope should be 10^{23} g , several hundred years will be required for accreting this amount of matter. Assuming that the number of isolated neutron stars with such high rate is 10^5 (Blaes & Madau 1993), one should expect 10–100 fast X-ray transients per year.

3.2. The longer duration X-ray transients

With the exception of GRS 1133+54, the other three sources quoted in Table 2 are concentrated near the galactic plane, suggesting that they could be more distant than the three fast X-ray transients mentioned above. In this case, no nearby dwarf star or RS CVn systems have been identified within the corresponding error boxes.

GRS 0817-524. No variable stars are catalogued in the error box. However, we note the presence of an X-ray source detected by *ROSAT*: 1RXS J081938.3-520421 is listed in the All-Sky Bright Source Catalogue (Voges et al. 1996), with coordinates R.A.(2000) = 8h19m38.3s, Dec(2000) = $-52^\circ 04' 21''$.

GRS 1148-665. Two variable stars lie within the error box: CY Mus (a RR Lyr type) and TW Mus (an eclipsing binary of W UMa type). We also note here the existence of a *ROSAT* All-Sky bright source: 1RXS J115222.9-673815, at R.A.(2000) = 11h52m22.9s, Dec(2000) = $-67^\circ 38' 15''$.

GRS 1624-375. No variable stars are reported within the error box. A 300-s optical spectrum taken in March 1997 at the 2.2-m ESO telescope of the possible candidate suggested by Castro-Tirado (1994) reveals that this is a M-star unrelated to GRS 1624-375 (Lehmann 1998). However there are three sources in the *ROSAT* Catalogue: 1RXS J162730.0-374929, 1RXS J162751.2-371923 and 1RXS J163137.0-380439.

Taking into account the *a priori* probability of finding such bright X-ray sources in the typical WATCH error boxes (~ 1.5 sources per error box), we conclude that none of the 1RXS sources is related to the longer duration X-ray Transients detected by WATCH.

In the *Ariel V* Catalogue of fast X-ray Transients, Pye & McHardy (1983) described 10 X-ray transients with durations ranging 0.5–4 days. Some of them were associated with known Be-neutron stars systems, like 4U 0114+65, and other with RS CnV systems, like σ Cen or DM UMa (for which a flare lasting 1.5 days was observed by HEAO-2). The *RossixTE* satellite has recently detected other two X-ray transients: XTE J0421+560 and XTE J2123-058. XTE J0421+560 lasted for ~ 2 days (Smith et al. 1998) and it is probably related to a black hole in a binary system. XTE J2123-058 lasted for ~ 5 days and is presumably related to a low-mass binary in which a neutron star undergoes

type-I bursts (Levine et al. 1998, Takeshima and Strohmayer 1998). Another short-duration event, lasting ~ 2 days has been observed in X-rays and radio wavelengths in the superluminal galactic transient GRS 1915+105 (Waltman & Ghigo 1998). We consider that the three long duration events reported in this paper, with fluxes in the range 0.35–0.5 Crab assuming a Crab-like spectrum, are likely to have originated from compact objects in low-mass or high-mass X-ray binaries, similarly to XTE J0421+560 and XTE J2123-058.

4. Conclusions

Amongst the 3 fast X-ray transients discovered by WATCH in 1990-92, GRS 1100-771 might be related to a superflare arising from a YSO in the Chamaeleon I cloud, that would make -to our knowledge- the strongest flare ever seen in such an object. But the possibility of GRS 1100-771 being an isolated neutron star unrelated to the cloud cannot be excluded, given the relatively large error box provided by WATCH. None of the 3 longer duration X-ray transients seem to be related to known objects, and we suggest that they are likely to have originated from compact objects in low-mass or high-mass X-ray binaries.

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