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Long-term soft X-ray characterization of Supergiant Fast X-ray Transients: the cumulative luminosity distributions

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We constructed the cumulative luminosity distributions of most supergiant fast X-ray transients (SFXTs) and the classical supergiant X-ray binary (SgXB) IGR J18027-2016 by taking advantage of the long term monitoring of these sources carried out with *Swift*/XRT (0.3-10 keV). Classical SgXBs are characterized by cumulative distributions with a single knee around $\sim 10^{36}$-10^{37} erg s^{-1}, while all SFXTs are found to be significantly sub-luminous and the main knee in their distributions is shifted at lower luminosities ($\lesssim 10^{35}$ erg s^{-1}). As the latter are below the sensitivity limit of large field of view instruments opearating in the hard X-ray domain (>15 keV), we show that a soft X-ray monitoring is required to reconstruct the entire profile of the SFXT cumulative luminosity distributions. The difference between the cumulative luminosity distributions of classical SgXBs and SFXTs is interpreted in terms of different wind accretion modes.

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1. Introduction

Most of the so-called "classical" Supergiant X-ray binaries (SgXBs) host a neutron star (NS) accreting material from the wind of its O-B supergiant companion. These sources are characterized by a nearly persistent X-ray luminosity of L_X=10^{35}-10^{37} erg s^{-1} (mostly depending on their orbital period) and display variations in the X-ray intensity by as large as a factor of ∼20-50 on time scales of hundreds to thousands of seconds. This pronounced variability is usually ascribed to the presence of inhomogeneities in the accreting medium ("clumps").

Supergiant Fast X-ray transients (SFXTs) are a sub-class of SgXBs, displaying a much more pronounced variability in the X-ray domain: they spend most of their time in low luminosity states (L_X=10^{32}-10^{33} erg s^{-1}) and only sporadically undergo a few-hours long outbursts reaching peak luminosities comparable to the persistent level of other SgXBs (Sguera et al., 2006). As inhomogeneities in the accreting material are not sufficient to account for such pronounced variability, the mechanism regulating the SFXT activity is still a matter of debate (see, e.g., Bozzo et al., 2013).

Large field-of-view (FoV) hard X-ray imagers, like the IBIS/ISGRI on-board *INTEGRAL* (20 keV-1 MeV; Ubertini et al., 2003; Lebrun et al., 2003) and *Swift*/BAT (15-150 keV Barthelmy et al., 2005), have been very efficient in catching a large number of sporadic SFXT outbursts. The long-term monitoring data now available have been exploited to estimate the SFXT activity duty-cycle (see, e.g., Romano et al., 2014a; Paizis & Sidoli, 2014, hereafter P14). The latter was found to be significantly lower (1-5 %) in the hard X-ray domain than that of classical SgXBs (∼80 %). By using all archival ISGRI data, P14 also reported a detailed comparison between the cumulative luminosity distributions of these two classes of sources. They showed that in the energy range 17-50 keV the distributions of SFXTs can be reasonably well described by a single power-law, while those of classical SgXBs are typically more complex, showing a knee at luminosities ∼10^{36} erg s^{-1} and requiring at least two different power-laws to satisfactorily describe their profiles.

The fainter states of SFXTs can be studied within a reasonable sensitivity only by using pointed observations with focusing X-ray telescopes. Among these, XRT (Burrows et al., 2005) on-board *Swift* proved to be particularly useful in carrying out long-term monitoring of the SFXTs, as it can take advantage of the unique scheduling flexibility of the *Swift* satellite (Gehrels et al., 2004). For most of the SFXTs, bi-weekly observations lasting 1 ks and achieving a limiting sensitivity comparable to their lowest emission level have been carried out from 2007 to present (Sidoli et al., 2008; Romano et al., 2009, 2011). These data provide now a sufficiently long baseline to be compared with the results obtained through wide FoV hard X-ray imagers. A first comparison was reported by Romano et al. (2014b, hereafter R14), who showed that XRT data allow us to estimate the SFXT duty cycle across 4 orders of magnitude in X-ray luminosity. In this letter, we concentrate on their soft X-ray cumulative luminosity distributions.

2. *Swift* sample and data analysis

We made use of all available XRT data collected from 2007 to 2013 from the 10 SFXTs reported below. This data-set has been presented in Bozzo et al. (2014) and comprises:
- data from the monitoring of the SFXTs IGR J16479-4514, XTE J1739-302, and IGR J17544-2619 collected from 2007-10-26 to 2009-11-03;

- data from the monitoring of AX J1841.0-0536 collected from 2007-10-26 to 2008-11-15;
- data from the monitoring of one complete orbit of the SFXTs IGR J18483-0311 (carried out from 2009-06-11 to 2009-07-08), IGR J16418-4532 (carried out from 2011-02-18 to 2011-07-30), and IGR J17354-3255 (carried out from 2012-07-18 to 2012-07-28);
- data accumulated during the most recent monitoring campaigns of the SFXTs IGR J08408-4503, IGR J16328-4726, and IGR J16465-4507. These campaigns have been carried out from 2011-10-20 to 2013-10-24.

In order to compare results from the SFXTs to those of classical neutron star SgXBs, we also analyzed XRT data obtained during a monitoring campaign of IGR J18027-2016 (for a detailed log of the data used, see Bozzo et al., 2014). This is a classical eclipsing SgXBs with an orbital period of 4.57 days. The neutron star spin period is 139.47 s (Hill et al., 2005), and the companion star was classified as a B0-BI supergiant located at a distance of 12.4 kpc (Mason et al., 2011). The XRT monitoring campaign covered 7 orbital periods of the source with daily pointings of 1–2 ks in Photon counting (PC) mode. These observations also provided the most accurate source position to date for this source at RA(J2000) = 270.67494, Dec(J2000) = −20.28813 (estimated uncertainty 1.4" radius). We extracted from the XRT data the 0.3–10 keV background-subtracted lightcurve (100 s resolution) and the average spectrum. The latter could be fit ($\chi^2_{\rm red}$/d.o.f. = 0.97/98) by using an absorbed power-law model with a column density of $(2.6\pm0.2)\times10^{22}$ cm^{-2} and a photon index of Γ = 0.43±0.09. An emission Fe Kα line was also added to the fit. The estimated centroid energy of the line is 6.39±0.06 keV and the corresponding equivalent width ∼0.1 keV.

3. XRT cumulative luminosity distributions

We created the cumulative luminosity distributions of all sources considered in this work by using the corresponding XRT lightcurves binned at 100 s. Observations where a significant detection of the source (≥3 σ) was not achieved in 100 s were excluded from further analysis (including time intervals corresponding to X-ray eclipses, where relevant). For all SFXTs, we used the same distances as R14 to convert from count-rates to luminosity and the 2-10 keV unabsorbed flux of each source. The conversion for IGR J18027-2016 was calculated by adopting the parameters obtained from the fit to the mean source spectrum. The cumulative luminosity distributions of all SFXTs that have been monitored at least for one orbital period by XRT and that of IGR J18027-2016 are shown in Fig. 1 with 100 bins per decade in luminosity. We need to distinguish the following cases: (i) IGR J16479−4514, XTE J1739−302, and IGR J17544−2619 went into outburst during the corresponding observing campaigns, so the data shown in the top panel of Fig. 1 include all luminosity levels experienced by these sources; (2) IGR J08408−4503, IGR J16328−4726, and AX J1841.0−0536 did not experience an outburst during the monitoring, but outbursts were recorded at different times (R14). To assess their overall distributions, we thus also added the data of such outbursts and plotted the corresponding distributions in the bottom panel of Fig. 1. This does not affect our conclusions.

All cumulative luminosity distributions in Fig. 1 were also normalized to the total exposure time of each source, such that the source DC correspond to the highest value on the y-axis and an easier comparison can be carried out with the cumulative distributions obtained in the hard X-rays (P14). By comparing our Fig. 1 with Fig. 1 in P14, we first notice that the cumulative distributions

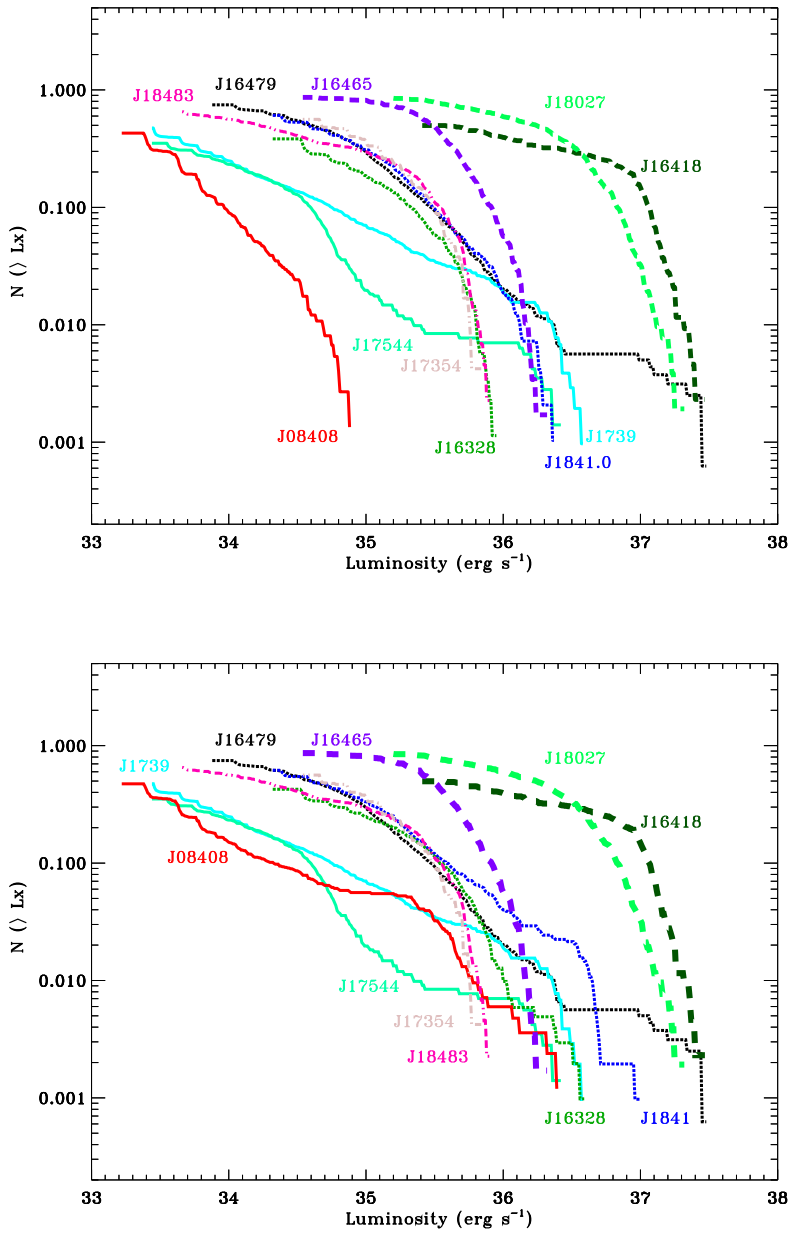

Figure 1: Top: cumulative luminosity distributions of all sources considered in this work. The distributions are constructed in the 2-10 keV energy band but using only XRT data collected during the monitoring campaigns of all sources. Bottom: same as for the figure on the top, but in this case we also considered for the sources IGR J08408−4503, IGR J16328−4726, and AX J1841.0−0536 the outbursts recorded by XRT outside the corresponding monitoring campaigns. In both cases we represented the cumulative luminosity distributions of classical SgXBs with thicker dashed lines (including IGR J16418−4532 and IGR J16465−4507, and used dot-dashed lines for the intermediate SFXTs. The distributions of SFXTs have been represented with dotted lines, while solid lines have been used for the three most extreme SFXTs IGR J08408−4503, XTE J1739-302, and IGR J17544-2619.

of SFXTs in the soft X-rays do not have power-law shaped profiles. More precisely:

- the source IGR J18027-2016 is characterized by a cumulative distribution with a single knee around 10^{36} erg s^{-1}, as expected for classical SgXBs.

- the distributions of IGR J16465-4507 and IGR J16418-4532 closely resemble those of classical SgXBs. In the logN-logL plot, a knee is observed at a certain critical luminosity and the slope of the profile changes abruptly above this value. Similar profiles were observed by P14 in the cases of Vela X-1 and 4U 1700-377. The only difference seems to be that the IGRs mentioned above are at a distance much larger than that of Vela X-1 and 4U 1700-377. Their fluxes are thus too low (by a factor of $\gtrsim$100) for the wide FoV instruments to exploit their entire X-ray dynamical range. The higher sensitivity of XRT allows us to follow more accurately their activity and the complete profile is recovered. Interestingly, IGR J16465-4507 and IGR J16418-4532 have been recently classified as classical SgXBs rather than SFXTs by R14 and Drave et al. (2013), respectively. Our results support this re-classification, and thus these two sources should be considered from now onward as part of the classical SgXBs. The cumulative luminosity distributions of all classical SgXBs in Fig. 1 have been plotted with thicker dashed lines.

- IGR J18483-0311 and IGR J17354-3255 have similar distributions as classical SgXBs, but their overall profile and the knees appear to be shifted at lower luminosities ($\sim10^{35}$ erg s^{-1}). These two sources are classified as "intermediate" SFXTs, and are thus thought to be the missing link between the SFXTs and classical SgXBs (due to their reduced dynamic range in the X-ray luminosity; see, e.g., Rahoui & Chaty, 2008; Giunta et al., 2009; Ducci et al., 2013). The cumulative luminosity distributions of these two sources have been plotted in Fig. 1 by using dot-dashed lines.

- A similar conclusion as above applies to the cumulative luminosity distributions of the SFXTs IGR J16479-4514, IGR J16328-4726, and AX J1841.0-0536. The reduction in the average luminosity of IGR J16479-4514 and IGR J16328-4726 is evident once a comparison is carried out with, e.g., IGR J16418-4532 in the present paper and Vela X-1 in P14, respectively (note that Vela X-1 as an orbital period close to IGR J16328-4726, while IGR J16418-4532 has a period similar to IGR J16479-4514). No orbital period is known yet in the case of AX J1841.0-0536. The cumulative luminosity distributions of these SFXTs are plotted in Fig. 1 with dotted lines.

- the cumulative luminosity distributions of the SFXT prototypes IGR J17544-2619, XTE J1739-302, and IGR J08408-4503 are shifted to even lower luminosities than other sources in this class. These three objects also display somewhat more complex profiles, and the identification of a knee is not trivial as in all other cases. We used solid lines in Fig. 1 to represent the luminosity distributions of the three SFXT prototypes.

Given the complex variety of all the cumulative distribution profiles, we did not attempt to fit them with some phenomenological model (e.g. a single or broken power-law). Instead, we show below how the shape of these profiles gives precious insights on the physical mechanisms regulating the X-ray activity of classical SgXBs and SFXTs.

4. Discussion and conclusions

We made use of the long-term monitoring observations performed with the XRT on-board *Swift* to construct for the first time the cumulative luminosity distributions of most of the currently known SFXTs and a few classical SgXBs. Because of the re-classification of the sources IGR J16418-4532 and IGR J16465-4507, the cumulative luminosity distribution of three classical SgXBs can be presently constructed by using XRT data. The profile of these distributions closely resembles those of other classical SgXBs monitored in the hard X-rays and reported by P14 (see, e.g, the cases of Vela X-1 and 4U 1700-377). This similarity suggests that the cumulative distributions of all classical SgXBs is generally characterized by a profile featuring a single-knee. The latter occurs at luminosities of $\sim 10^{36}$-10^{37} erg s^{-1}.

Single-knee profiles can be relatively well understood in terms of wind accretion from an inhomogeneous medium. Fürst et al. (2010) showed that the X-ray luminosity of a system in which the NS is accreting from a highly structured medium, rather than a smooth wind, is expected to have a typical log-normal distribution. The profile of the corresponding cumulative distribution would thus be characterized by the presence of a single knee. Structures in the winds of a supergiant star are usually associated with "clumps", i.e. regions endowed with larger densities (a factor of $\sim$10) and different velocities (a factor of few) with respect to the surrounding medium (Owocki et al., 1988). These structures can be as large as ~ 0.1 R$_*$ (here R$_*$ is the radius of the supergiant star; see, e.g., Dessart & Owocki, 2002, 2003, 2005; Šurlan et al., 2013). According to the classical picture of wind accreting systems (see, e.g., Frank et al., 2002, and references therein), the variation in the local density and/or velocity around a compact object produced by a clump can give rise to rapid changes in the mass accretion rate and thus on the released X-ray luminosity. Accretion from a moderately clumpy wind can thus qualitatively explain the X-ray variability of SgXBs and the profile of their cumulative luminosity distributions.

Oskinova et al. (2012) showed that, despite the remarkable variations in the X-ray luminosity that can be produced by accretion from a highly inhomogeneous medium, the long-term averaged luminosity of the system is comparable to that obtained in the case of a smoothed-out wind. It is thus expected that the position of the knee in the cumulative luminosity distribution of a SgXB, being roughly associated to the value of its averaged X-ray luminosity, will mainly depend on its orbital period: the closer the NS to its companion, the higher the expected averaged X-ray luminosity[1] (due to the enhanced density and slower velocity of the wind). This trend seems to be qualitatively respected by the classical SgXBs in our Fig. 1 and in Fig. 1 of P14. As an example, the knee of IGR J16418-4532, which is characterized by an orbital period of 3.4 days, is located at a higher luminosity with respect to that of IGR J18027-2016, which has a larger orbital period (4.5 days). The same is true if the comparison is carried out between IGR J18027-2016 and Vela X-1 (orbital period 8.9 days), and if the even larger orbital period of IGR J16465-4507 is taken into account. Additional XRT monitoring observations of classical SgXBs are currently being planned in order to confirm these findings.

[1] We neglected here the eccentricity, photo-ionization of X-rays on the supergiant wind and other processes that can affect the overall X-ray luminosity (see, e.g., Ducci et al., 2010, and references therein). A detailed treatment of these effects is beyond the scope of the present paper.

According to the discussion above, it is unlikely that a simplified accretion wind scenario including only the presence of clumps could explain the X-ray behavior observed from the SFXT sources. Clumps provide, in principle, the means to trigger SFXT outbursts, but they cannot account for the substantial lower luminosity of these sources compared to classical SgXBs. To corroborate this argument, we first consider the cumulative distributions of the intermediate SFXTs IGR J18483-0311 and IGR J17354-3255, which are thought to be the missing link between classical systems and the SFXT prototypes. The profile of the distributions displayed by these two sources are similar to those of classical SgXBs, but are shifted toward the lower left side of the plots in Fig. 1. As an example, IGR J17354-3255 is characterized by an orbital period close to that of Vela X-1, but its average X-ray luminosity is a factor of $\sim$10 lower (see Fig. 1 in P14). This problem worsens when the cumulative luminosity distributions of the other SFXTs are considered. All SFXTs observed by XRT appear to be on-average much less luminous than the classical SgXBs. It is particularly worth mentioning the case of IGR J16479-4514 which has an orbital period similar to that of IGR J16418-4532 but its luminosity distribution is shifted at an average luminosity that is roughly a factor of $\sim$100 lower. The same conclusion would be reached by comparing the SFXT prototype IGR J17544-2619 with IGR J18027-2016 which have similar orbital periods (note that the relatively small uncertainties on the distance to all sources considered here would not be able to compensate for the estimated differences in luminosity; see Table 6 in R14). Beside being characterized by the lowest average luminosity, the three SFXT prototypes show also cumulative luminosity distributions with relatively complex profiles. In these cases, it is not trivial to accurately identify the main knee of their distribution.

It is interesting to note that the distributions of all SFXTs in Fig. 1 would clearly lead to low activity DCs for these objects when observed through low sensitivity large FoV instruments[2]. The latter are, indeed, not able to probe the rapid increases of the cumulative luminosity distributions of these sources in their fainter luminosity states, thus permitting us to study only the power-law shaped decay above $\gtrsim 10^{35}$ erg s^{-1} (see P14).

The mass loss rate of supergiants is known to have a significant spread depending on the star properties (Vink et al., 2000; Puls et al., 2008). However, the fact that all SFXTs are characterized by similar companion stars to those in classical SgXBs (Rahoui & Chaty, 2008) but are significantly sub-luminous compared to them, suggests a difference in the accretion processes on-going in these sources rather then a systematic discrepancy in the physical properties of their stellar winds (e.g., clumping factors). In order to produce a large decrease in the long-term X-ray luminosity, a mechanism is required to inhibit at least part of the accretion toward the NS and regulate plasma entry within the compact star magnetosphere. Theoretical models suggested so far to interpret the X-ray variability of SFXTs provide different ways to account for this feature.

In the models proposed by Grebenev & Sunyaev (2007) and Bozzo et al. (2008), the inhibition of accretion is provided by the onset of centrifugal and/or magnetic barriers. The latter are due to the rotation and magnetic field of the NS. Depending on the strength of this field and the value of the spin period, the onset of different accretion regimes can lead to a substantial variation of the overall source luminosity (a factor of 10^4-10^5). The switch from one regime to another is triggered by the

[2]The sensitivity limit is different for each source, as it depends on the intrinsic flux and the exposure time considered. We refer the reader to P14 for an exhaustive discussion regarding the ISGRI sensitivity limits for the observations of SFXTs.

interaction of the NS with moderately dense clumps. Assuming typical parameters of supergiant star winds, the largest variability is achieved when the magnetic barrier is at work. The latter requires intense magnetic fields ($\gtrsim 10^{14}$ G) and long spin periods ($\gtrsim$1000 s). While the magnetic gating would easily provide the means to achieve an X-ray variability comparable to that shown by the SFXT prototypes, the recent discovery of a cyclotron line at ∼17 keV from IGR J17544-2619 (suggesting a NS magnetic field intensity as low as $B \simeq 10^{12}$ G) raised questions on the applicability of the magnetic gating model at least to this source (Bhalerao et al., 2014).

In the quasi-spherical settling accretion model proposed by Shakura et al. (2012), the inhibition of accretion is provided by a hot quasi-static shell that forms above the NS magnetosphere when a sufficiently low mass accretion rate is maintained. A substantial average reduction (a factor of ∼30) of the mass accretion rate onto the NS (and thus X-ray luminosity) is expected if the plasma entry through the compact star magnetosphere from the shell is regulated by inefficient radiative plasma cooling. If Compton cooling dominates, a reduction of the mass accretion rate by a factor of ∼3 is achieved (Shakura et al., 2013). The bright SFXT flares are proposed to result from sporadic reconnections between the NS magnetosphere and the magnetic field embedded in the stellar wind. According to this model, the main difference between SgXBs and SFXTs would thus be that only for the latter sources the wind properties are such that a low density is stably maintained around the compact object (e.g., through a systematically lower mass loss rate from the supergiant star or higher/lower wind velocity/density) and magnetized stellar winds play a role in triggering large accretion episodes (Shakura et al., 2014). However, such requirements are difficult to accommodate, given the lack of any clear evidence of systematic differences between stellar winds in SFXTs and classical SgXBs (see Sect. 1). Further theoretical studies are currently ongoing to investigate these issues.

Finally we note that the cumulative luminosity distributions of the SFXT prototypes reported in Fig. 1 feature the presence of plateau and multiple knees and thus look more complex than the profiles of other SFXTs and classical systems. At present we cannot exclude that these plateau are due to the relatively low number of bright SFXT outbursts recorded by XRT, which limits the completeness of the cumulative distributions at the higher luminosities ($\gtrsim 10^{36}$ erg s^{-1}; see also R14). In case future outbursts detected by XRT during our monitoring campaigns will be discovered to span a relatively large range in luminosity at the peak (e.g., a factor of 10 or more in the same time bin considered here), the decay of the cumulative luminosity distributions could be significantly affected (this would not change the sub-luminosity problem discussed before). However, it is noteworthy that the ∼12 years monitoring campaigns carried out with the *RXTE*/PCA on several SFXTs also feature plateau. Although the plateau in the PCA data are less prominent than those observed by XRT, in both cases these features are due to the brightest SFXT outbursts which are detected as rare events and span a relatively limited range in luminosity (Smith et al., 2012). If consolidated by future XRT monitoring observations, this could be interpreted in terms of those peculiar source states discussed above during which the highest mass accretion rate is achieved.

We conclude that the currently available XRT data provide support in favor of the general features of the theoretical models proposed so far to interpret the SFXT behavior, but do not allow yet to distinguish between them. A number of open questions remain to be investigated theoretically in the near future, including the requirement of strong magnetic fields for the applicability of the

magnetic gating and the need for systematic differences in stellar wind parameters in the settling accretion model.

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