A detailed study of the 5-Hz quasi-periodic oscillations in the bright X-ray transient and black hole candidate GRS 1739–278

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ABSTRACT

We present a detailed study of the 5-Hz quasi-periodic oscillation (QPO) recently discovered in the bright X-ray transient and black hole candidate (BHC) GRS 1739–278 (Borozdin & Trudolyubov) during a Rossi X-ray Timing Explorer observation taken on 1996 March 31. In total 6.6 ksec of on-source data were obtained, divided in two data sets of 3.4 and 3.2 ksec which were separated by ~2.6 ksec. The 5-Hz QPO was only present during the second data set. The QPO increased in strength from below 2 per cent rms amplitude for photon energies below 4 keV to ~5 per cent rms amplitude for energies above 10 keV. The soft QPO photons (below 5 keV) lagged the hard ones (above 10 keV) by almost 1.5 rad. Besides the QPO fundamental, its first overtone was detected. The strength of the overtone increased with photon energy (from <2 per cent rms below 5 keV to ~8 per cent rms above 10 keV). Although limited statistics did not allow for an accurate determination of the lags of the first overtone, indications are that also for this QPO the soft photons lagged the hard ones. When the 5-Hz QPO was not detected (i.e., during the first part of the observation), a broad noise component was found for photon energies below 10 keV but it became almost a true QPO (with a Q value of ~1.9) above that energy, with a frequency of ~3 Hz. Its hard photons preceded the soft ones in a way reminiscent of the 5-Hz QPO, strongly suggesting that both features are physically related. We discuss our finding in the framework of low-frequency QPOs and their properties in BHCs.

Key words: accretion, accretion discs – stars: individual: GRS 1739–278 – X-rays: stars.

1 INTRODUCTION

Before the launch of the Rossi X-ray Timing Explorer (RXTE), the usual picture for black hole candidates (BHCs) was simple and one-dimensional: the changes in the X-ray spectra and the rapid X-ray variability are caused by changes in the mass accretion rate \( \dot{M} \) (Tanaka & Lewin 1995; van der Klis 1995). In the BHC low state (LS), \( \dot{M} \) is low and the spectra are hard. The LS power spectra are dominated by a very strong (20–50 per cent rms amplitude) band-limited noise which approximately follows a power law with index 1 at high frequencies, but below a certain frequency (the break frequency) the power spectrum becomes roughly flat. Above this frequency a broad bump or a quasi-periodic oscillation (QPO) is often present, although also QPOs with similar frequencies as the break frequency are observed. In some sources, a second break is visible in the power spectrum, above which the power-law index increases to about ~2. In the high state (HS), \( \dot{M} \) is higher, the spectra are much softer, and in the power spectra only a weak (a few per cent) power-law noise component is present. In the very high state (VHS), \( \dot{M} \) is the highest, the spectra are harder but not as hard as in the LS, and in the power spectra, noise is present similar to either the weak HS noise or the LS band-limited noise (although only with a strength of 1–15 per cent rms). QPOs near 6 Hz are detected sometimes with a complex harmonic structure.

With the many observations performed with RXTE on BHCs, the behaviour of BHCs turned out to be much more complex than previously thought. First of all, RXTE has expanded the range of frequencies at which the BHCs show variability up to 450 Hz (e.g., Remillard et al. 1999a,b; Cui et al. 2000; Homan et al. 2001; Strohmayer 2001). The nature of these BHC high-frequency QPOs is unclear, although it has been suggested that they might be related to the twin kHz QPOs in the neutron star systems (Psaltis, Belloni & van der Klis 1999). Also, with RXTE in many BHCs the VHS has now been detected and the associate low-frequency (<20 Hz) QPOs have been found (e.g., Remillard et al. 1999b; Borozdin &

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Trudolyubov 2000; Cui et al. 2000; Dieters et al. 2000; Revnivtsev, Trudolyubov & Borozdin 2000; Homan et al. 2001), indicating that these QPOs are a common feature of BHCs. The phenomenology of these QPOs is very complex and they are observed during different luminosity levels (at levels significantly below the highest observed luminosities, i.e., not only during the VHS but also at states intermediate between the LS and the HS; e.g., Homan et al. 2001). The phenomenology of these QPOs is such that even in individual sources, the QPO inter-relationships are not fully understood (see, e.g., Wijnands, Homan & van der Klis 1999 or Homan et al. 2001). The relationship between the QPOs observed in different BHCs is even less well understood. However, from a detailed study of the state behaviour in XTE J1550–564 it is clear that the one-dimensional picture described above for the BHC states (depending only on $M^\dot{\!}$) does not hold in this particular source and another extra parameter is needed to explain its behaviour (Homan et al. 2001). Similar behaviour might also be observable for the other BHCs; however, not much information about this is presently available.

One of the most recent additions to the collection of BHCs which exhibit QPOs near 6 Hz is the X-ray transient and BHC GRS 1739–278. At the end of 1996 March, this new X-ray transient was discovered with the SIGMA telescope on board Granat (Paul et al. 1996; Vargas et al. 1997). Soon after the discovery of this new X-ray source its radio and optical counterparts were discovered (Hjellming et al. 1996; Mirabel et al. 1996; Marti et al. 1997). From a ROSAT observation of the source an extinction of $A_v = 14 \pm 2$ was derived, implying that the source is located at a distance of 6–8.5 kpc and that it was radiating at least near the Eddington limit for a 1-M$_\odot$ compact object (Dennerl & Greiner 1996; Greiner, Dennerl & Predehl 1996). In X-rays, GRS 1739–278 was studied by the TTM experiment on board Mir-Kvant and by the PCA instrument on board RXTE (Borozdin, Alexandrovich & Sunyaev 1996; Takeshima et al. 1996; Borozdin et al. 1998). The RXTE data showed that on 1996 March 31, the source was in the canonical black hole VHS and the RXTE observations taken in 1996 May showed that the source had transit to the canonical HS. Recently, Borozdin & Trudolyubov (2000) reported the discovery of a 5-Hz QPO during the 1996 March 31 RXTE observation. Because the QPO behaviour of BHCs is not well understood, we decided to study the properties of this 5-Hz QPO in GRS 1739–278 in more detail (e.g., time variability, phase lags).

2 OBSERVATION AND ANALYSIS

RXTE observed GRS 1739–278 on several occasions during its 1996 outburst. For a detailed overview of the RXTE observations, we refer to Borozdin et al. (1998). In this paper, we concentrate on

![Figure 1](https://academic.oup.com/mnras/article-abstract/328/2/451/1085544)
the 1996 March 31 observation during which the 5-Hz QPO was
discovered (Borozdin & Trudolyubov 2000). In order to avoid
confusion with the bright neutron star X-ray transient GRO
J1744–28, the satellite was not directly pointed at GRS 1739–278
but had an off-set pointing of ~11 arcmin (see Takeshima et al.
1996; Borozdin et al. 1998). Borozdin & Trudolyubov (2000)
showed that the QPO almost certainly originated from GRS
1739–278 and not from GRO J1744–28.

During the 1996 March 31 observation, data were simul-
taneously collected in the Standard2f mode (129 photon energy
channels with 16-s time resolution), in the single bit modes
SB_125US_0_13_1S and SB_125US_14_35_1S (1 photon energy
channel, 128-μs time resolution), in the binned mode
B_2MS_16A_0_35_Q (16 photon energy channels, 2-ms time
resolution), and in the event mode E_16US_64M_36_1S (64
photon energy channel, 16-μs time resolution). We used the
Standard2f data to create a light curve and the colours. For this
analysis, we only used the data during which all five detectors were
on; because of this restriction, we disregarded the first ~1000 s of
the observation during which two out of the five detectors were off.
For the analysis of the rapid X-ray variability we used all the data
available, unless otherwise noted. The high time resolution modes
(single bit, binned, and event mode data) were used to calculate
discrete Fourier transforms between 1/16–4096 and 1/16–256 Hz,
from which the power and cross spectra were calculated. The
power spectra were fitted with a constant (representing the dead-
time modified Poisson noise), a power law (for the low-frequency
noise component), and one or more Lorentzians (for the peaked
noise component and the QPOs). The uncertainties in the fit
parameters were calculated using Δχ^2 = 1 and upper limits using
Δχ^2 = 2.7 which yields 95 per cent confidence levels. The phase
lags of the QPOs were calculated for a frequency interval equal to
the full width at half-maximum (FWHM) of the Lorentzians used
to fit the QPOs, centred on the peak frequency of these Lorentzians.
To correct for the small dead-time effects on the phase lags, we
subtracted the average 50–125 Hz cross vector from the cross
spectra (see van der Klis et al. 1987). The single bit and the event
mode data were used to search for high-frequency (>100 Hz) QPOs.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** The 2–60 keV light curve (a), the soft colour (b), and the hard colour (c) of GRS 1739–278 on 1996 March 31. The first ~1000 s of the observation were not used because only three out of the five detectors were on. The soft colour is the 3.7–6.2 keV/2.2–3.7 keV count rate ratio and hard colour the 6.2–16.2 keV/2.2–3.7 keV count rate ratio. The time resolution for the light curve is 16 s in order to show the rapid count rate variations. The time resolution of the colours is 256 s in order to decrease the errors on the colours. The count rates were corrected for background and off-set (the collimator correction factor was 1.1572) but not for dead-time (~15 per cent). The gap in the data is because of an Earth occultation of the source and a passages of the satellite through the SAA.

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3 RESULTS

3.1 Light curve and colours

The RXTE all sky monitor (ASM\(^1\)) light curve (1.5–12 keV) of the source is shown in Fig. 1(a) (see also Borozdin et al. 1998; Borozdin & Trudolyubov 2000). The outburst light curve of GRS 1739–278 can be classified as a typical fast rise, exponential decay light curve, although with multiple maxima in the decay. At the peak of the outburst the flux was about 1 Crab, which makes this source a bright X-ray transient. The 5–12 keV/2.2–3.7 keV count rate ratio curve is shown in Fig. 1(b), which shows that the spectrum was hardest at the start of the outbursts (during the rise, before the peak of the outburst) and gradually became softer. The 5-Hz QPO was discovered during the 1996 March 31 RXTE observation, which is day 90 in this figure, at a time when the source was already considerable weaker than at the peak of the outburst, and the X-ray spectrum had significantly softened compared to previous days.

The 2–60 keV light curve of the RXTE/Proportional Counter Array (PCA) observation of 1996 March 31 is shown in Fig. 2(a). The gap between the two parts of the light curve is because of an Earth occultation of the source and a passage of the satellite through the South Atlantic Anomaly (SAA). The light curve has been corrected for the instrument off-set (the collimator correction factor was 1.1572). In Figs 2(b) and (c), the soft and the hard colour curves are shown, respectively. As soft colour we used the 3:7–6:2 keV/2:2–3:7 keV count rate ratio and as hard colour we used the 6:2–16:2 keV/2:2–3:7 keV count rate ratio. From Fig. 2(a), it is apparent that the source was highly variable on time-scales of minutes. Also, it can be observed that, although the source count rate was gradually decreasing on time-scales of weeks, the count rate increased with time during this observation, which is most clearly visible in the second part of the observation. The soft colour (Fig. 2b) did not show a clear correlation with time, whereas the hard colour (Fig. 2c) clearly increased with time (best visible in the second part of the observation). Because the count rate also increased with time (Fig. 2a), in the ‘hard’ hardness–intensity diagram (HID; as colour the hard colour was used; Fig. 3b), the hard colour showed a clear positive correlation with the count rate, but in the ‘soft’ HID (as colour the soft colour was used; Fig. 3a), the soft colour did not show such a good correlation (as expected from the lack of a good correlation of the soft colour with time). Thus, the soft colour seemed to increase slightly with count rate. This is reflected in the colour–colour diagram (CD; Fig. 4) which shows that the soft colour actually decreased when also the hard colour increased.

\(^1\)The quick-look ASM data used in this paper can be obtained from http://xte.mit.edu/ASM_lc.html and are provided by the ASM/RXTE team. See Levine et al. (1996) for a detailed description of the ASM.

Figure 3. Hardness–intensity diagrams (HIDs) of GRS 1739–278 on 1996 March 31: (a) the ‘soft’ HID and (b) the ‘hard’ HID. The first ~1000 s of the observation were not used because only three out of the five detectors were on. The soft colour is the 3.7–6.2 keV/2.2–3.7 keV count rate ratio and hard colour the 6.2–16.2 keV/2.2–3.7 keV count rate ratio. The time resolution is 256 s. The data were corrected for background. The solid dots are the data for the first part of the observation; the crosses for the second part.

Figure 4. Colour–colour diagram of GRS 1739–278 on 1996 March 31. The first ~1000 s of the observation were not used because only three out of the five detectors were on. The soft colour is the 3.7–6.2 keV/2.2–3.7 keV count rate ratio and hard colour the 6.2–16.2 keV/2.2–3.7 keV count rate ratio. The time resolution is 256 s. The data were corrected for background. The solid dots correspond to the first part of the observation; the crosses to the second part.
3.2 Rapid X-ray variability

In order to study the rapid X-ray variability (i.e., the 5-Hz QPO discovered by Borozdin & Trudolyubov 2000), we first produced a dynamical power spectrum of the data (Fig. 5). From this figure, it is apparent that the QPO was only clearly present in the second part of the data and not in the first part. To check this, we created a power spectrum for each part separately (shown in Figs 6a and b). Using the energy range 2.8–31.7 keV, a very significant 5-Hz QPO [rms amplitude 2.33 ± 0.07 per cent (∼18σ); frequency 5.09 ± 0.03 Hz, width 1.11 ± 0.09 Hz] and its first overtone [rms amplitude 1.9 ± 0.1 (∼9σ); frequency 10.2 ± 0.2 Hz; width...
2.7 ± 0.4 Hz] were present during the second part of the observation, but during the first part the 5-Hz QPO was not present (but see below), although a weak noise component around a few hertz was (see Fig. 6). During the second part, an extra noise component at low frequencies was also present which was fitted with a power law (rms amplitude 1.16 ± 0.09 per cent and with a power-law index of 0.71 ± 0.08).

To study the energy dependence of the rapid X-ray variability, we made power spectra of each part in a soft band (2–8.7 keV; Figs 6c and d) and a hard one (8.7–60 keV; Figs 6e and f). At first glance, the noise component in the first part of the observation did not show any clear dependence on energy (but see below), but the QPOs in the second part did: at low energies the fundamental was stronger than its overtone, but at higher energies they were of comparable strength. The exact dependence of the QPO amplitude on photon energy is shown in Fig. 7(a) for the fundamental and in Fig. 7(b) for the first overtone (see also Table 1). From these figures, it is clear that at the highest energies (>10 keV) the overtone was even stronger than the fundamental, demonstrating that the overtone had a steeper dependence on photon energy than the fundamental.

To study the behaviour of the QPO fundamental in the second part with count rate and colours, we used 256-s data segments to track the QPO parameters in time. The results are shown in Fig. 8.

The frequency of the QPO increased slightly when the count rate increased (Fig. 8a) but more strongly when the hard colour increased (Fig. 8b), suggesting that the hard colour is a better tracer of the QPO frequency than the count rate. The other parameters of the QPO (rms amplitude and FWHM) did not show clear correlations either with the count rate or the colours.

We calculated cross spectra in order to study the phase lags of the QPOs. The phase lags between two broad energy bands as a function of frequency is shown in Figs 6(g) and (h). Clearly the 5-Hz QPO had negative phase lags (Fig. 6h), meaning that the hard photons of the 5-Hz QPO preceded the soft ones. The phase lags of the 5-Hz QPO as a function of photon energy are shown in Fig. 7(c). The lags increased with increasing photon energy. The lowest energy bin is not shown because the QPO was not detected in this energy band. Using two broad energy bands, we find an ~3σ significant phase lag of ~0.26 ± 0.08 rad for the first overtone between the energy bands 2.8–8.7 and 8.7–60 keV. Although barely significant, this might indicate that also for the first overtone the hard photons preceded the soft ones.

Fig. 6(g) shows that the noise component around 3–5 Hz in the first part of the data also had negative phase lags. The profile in the phase lag diagram is rather narrow (narrower than the width of the noise component) and suggests that it might be because of a narrower noise component or even a QPO. To investigate this

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**Figure 6.** Leahy normalized (Leahy et al. 1983) power spectra of the first (a, c, and e) and second (b, d, and e) part of the observation in the energy range of 2–60, 2–8.7, and 8.7–60 keV, respectively. The Poisson level has not been subtracted. Cross spectra of the first (g) and second (h) part of the observation, calculated between 2.8–8.7 and 8.7–60 keV. Negative signs mean that the hard photons precede the soft ones.
possibility, we examined the power spectra of the first part of the data in great detail for different energy ranges. We found that the noise component becomes more peaked at higher energies until it was nearly a true QPO (with a Q value of \(\approx 1.9\); hereafter, we refer to this feature as QPO). In Fig. 9, the power spectrum of the first part of the data is shown [only when all five Proportional Counter Units (PCUs) were on] for the energy range 11.2–31.7 keV containing the QPO. Its strength was \(9.8^{+0.8}_{-0.7}\) per cent rms amplitude (6.7\(\sigma\) significance), its FWHM was \(1.7^{+0.5}_{-0.3}\) Hz, and its frequency was \(3.2 \pm 0.1\) Hz. Below 11.2 keV either this QPO was

Figure 7. The rms amplitude of the fundamental (a), the rms amplitude of the overtone (b), and the phase lags of the fundamental (c) versus photon energy. In (c) the reference band chosen was 4.3–5.0 keV. Negative signs mean that the hard photons precede the soft ones.

Figure 8. The frequency of the fundamental versus the 2–60 keV count rate (a) and the hard colour (b). The count rates were corrected for background and collimator off-set, but not for dead-time. The hard colour is the 6.2–16.2 keV/2.2–3.7 keV count rate ratio.
significantly broader or an extra noise component was present, which makes the QPO upper limits at lower energies difficult to obtain. A conservative upper limit can be given by assuming that all the power present is because of the QPO. This results in an upper limit of 4.5 and 1.1 per cent for the energy ranges 4.3–11.2 and 2–4.3 keV, respectively. The QPO phase lag between 2.8–8.7 and 8.7–60 keV was $\pm 2.4 \pm 0.2$ rad, whose absolute value is larger than the absolute value of the phase lag of the 5-Hz QPO (see Table 2). For both QPOs the hard photons precede the soft ones.

Recently, QPOs above 100 Hz were found in several BHCs, simultaneously with QPOs around 5–7 Hz (e.g., Cui et al. 2000; Homan et al. 2001). We searched the data for similar QPOs in GRS 1739–278, but none were found. The 95 per cent confidence upper limits between 100 and 1000 Hz are 2.3 (1.7 per cent rms) and 2.3 per cent rms (1.8 per cent rms), respectively for 2–60 and 4.3–60 keV, assuming a width of 150 Hz (the values for a FWHM of 50 Hz are given between brackets).

4 DISCUSSION

We present a detailed study of the 5-Hz QPO in the bright X-ray transient and BHC GRS 1739–278. This QPO was only observed during one RXTE observation (on 1996 March 31) during which the source was in a state that can be identified as a VHS (see also Borozdin et al. 1998). However, it is clear that the source was not at its highest possible luminosity demonstrating that VHS behaviour can also occur at low luminosities, similar to what has been found in other BHCs (e.g., Homan et al. 2001). We showed that only during the second part of the observation the 5-Hz QPO and its first overtone were prominently present. During the first part only a broad noise component was present for energies below 10 keV and a broad QPO near 3 Hz for energies above that. All the QPOs considerably increased in strength with increasing photon energies, and the phase lags for all the QPOs demonstrate that the hard photons preceded the soft ones by as much as 1.5–2.5 rad.

The similarities between the 3-Hz QPO and the 5-Hz QPO (see Table 2) strongly suggest that they are directly related to each other. Most likely, the 3-Hz QPO evolved in the 5-Hz QPO, during which the frequency of the QPO increased, the energy dependence of the QPO became less depended on energy, and the soft phase lag dropped from 2.5 to $\sim 1$ rad (between the energy ranges 2.8–8.7 and 8.7–60 keV). Unfortunately, this evolution occurred during an Earth occultation of the source and a passage of the satellite through the SAA, so a detailed study of this process could not be made. From the X-ray colours and the HIDs and CD, it is clear that a small but significant spectral difference is present between the

Table 2. The 3-Hz QPO versus the 5-Hz QPO.

| Frequency (Hz) | Amplitude 2–4.3 keV (% rms) | Amplitude 4.3–11.2 keV (% rms) | Amplitude 11.2–31.7 keV (% rms) | Phase lags $^a$ (rad) |
|---------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 3.2 ± 0.1     | <1.1                        | <4.5                        | 9.8 ± 0.8                   | $-2.4 \pm 0.2$              |
| 5.09 ± 0.02   | 1.3 ± 0.1                   | 3.15 ± 0.07                 | <4.5                        | $-1.01 \pm 0.06$            |

$^a$Between the energy bands 2.8–8.7 and 8.7–60 keV.
two parts of the observation, with the part containing the 5-Hz QPO slightly harder than the part with the 3-Hz QPO. This shows that a very slight change of the X-ray spectrum is accompanied by a significant change in the rapid X-ray variability. Whatever triggered this change, it only minorly affected the X-ray spectrum. This significant difference between the two parts of the observation also makes it clear that during the VHS of GRS 1739–278, the accretion processes involved are far from stable but they are very dynamic on a time-scale of less than an hour. The difference between the first part and second part of the observation was not reported by Borozdin & Trudolyubov (2000), most likely because they combined both parts together in their analysis without performing any time selections. The 5-Hz QPO parameters quoted by them are therefore contaminated by the inclusion of the first part of the data which does not contain this feature. Therefore, we report a significantly larger strength for the 5-Hz QPO and its first overtone than Borozdin & Trudolyubov (2000).

Recently, the phase lags of the low-frequency QPOs in BHCs have received a considerable amount of attention in the literature. However, so far the phenomenology of these QPOs and their phase lags in particular are far from understood. The lags have now been received a considerable amount of attention in the literature. The lags have now been received a considerable amount of attention in the literature. The lags have now been received a considerable amount of attention in the literature.

Several theoretical studies have tried to address the complicated phase lags behaviour of the low-frequency QPOs in BHCs (e.g., Böttcher & Liang 2000; Nobili et al. 2000; Böttcher 2001), but those studies have focussed on the QPOs in GRS 1915+105. It is unclear to what extent the overall very complex behaviour of this source is influencing its QPO behaviour. Extrapolation from models for the behaviour (i.e., the QPOs and their phase lag behaviour) of GRS 1915+105 to other BHCs might turn out to be difficult and subject to errors. At the moment, there is no model available which can explain the observed phase lags of the QPOs, the evolution of those lags for the individual sources, and the differences between QPO behaviour in the different BHCs. However, it is clear that a Comptonizing medium around the black hole (thought to produce the power-law tail in the spectrum) cannot explain the lags observed for the QPOs around 6 Hz, either due to Compton up- or down-scattering.

Recently, in several BHC transients QPOs above 100 Hz were found (e.g., Remillard et al. 1999a,b; Cui et al. 2000; Homan et al. 2001; Strohmayer 2001). Often, although not always, these QPOs are found simultaneously with low-frequency QPOs (<10 Hz).

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Tanaka Y., Lewin W. H. G., 1995, in Lewin W. H. G., van Paradijs J., with similar characteristics as the 5-Hz QPO in GRS 1739–278. Therefore, similar high-frequency QPOs might also be present in GRS 1739–278. However, a search for such QPOs did not result in a significant detection, but the upper limits on the presence of such QPOs are not very stringent. Although in some sources stronger high-frequency QPOs have been found (e.g., XTE J1859+226; Cui et al. 2000), in other sources the high-frequency QPOs were considerably weaker than our upper limits (e.g., XTE J1530–564; Homan et al. 2001). Therefore, we cannot exclude that high-frequency QPOs were present in GRS 1739–278.

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Although submitted to ApJ for publication and available on astro-ph, this paper has been retracted for publication because of two major problems with the proposed QPO model: (1) the energy needed for the QPO mechanism to work exceeded that of the available energy, and (2) the predicted energy dependence of the QPO was the opposite to that observed (Böttcher, private communication)
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