Optical–X-ray Anti-correlations in 3FGL J1544.6−1125 and Optical Behavior During Low-to-High Mode Transitions in Transitional Millisecond Pulsars

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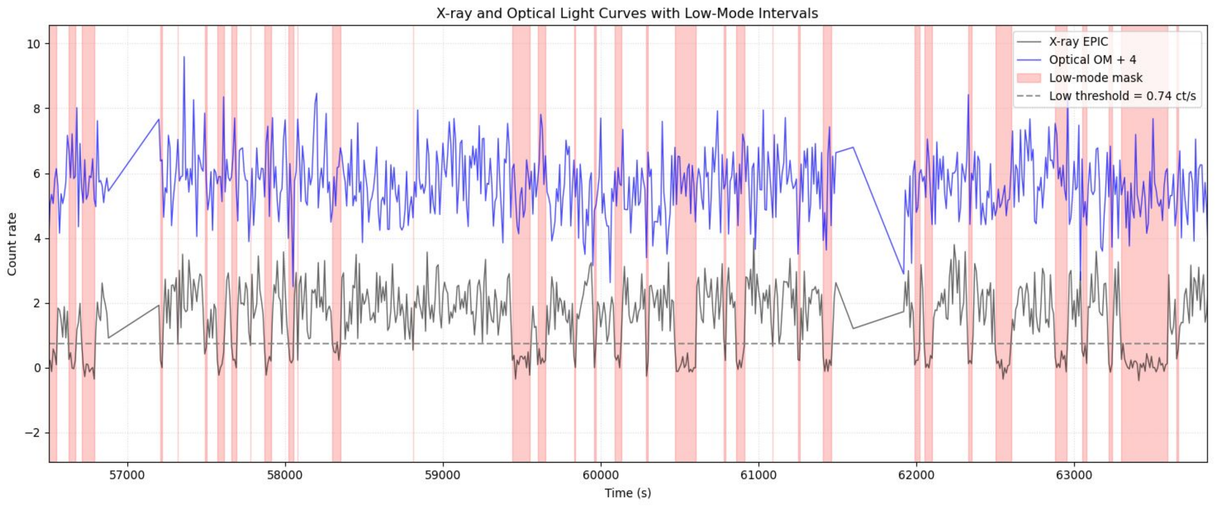
Abstract

Transitional millisecond pulsars (tMSPs) exhibit rapid switching between X-ray high and low modes, but the physical mechanism driving these transitions remains unclear. Using simultaneous XMM–Newton X-ray and optical observations, we investigate optical–X-ray anti-correlation in 3FGL J1544.6−1125, optical recovery following low-to-high transitions, and X-ray low-mode durations, with PSR J1023+0038 as a comparison source. J1544 shows only marginal evidence for optical–X-ray anti-correlation, while J1023 exhibits a significant optical return delay with a median of 20 s. The low-mode durations of both systems are broadly lognormal-like, although J1544 shows systematically shorter episodes.

Anti-correlations for 3FGL J1544.6−1125

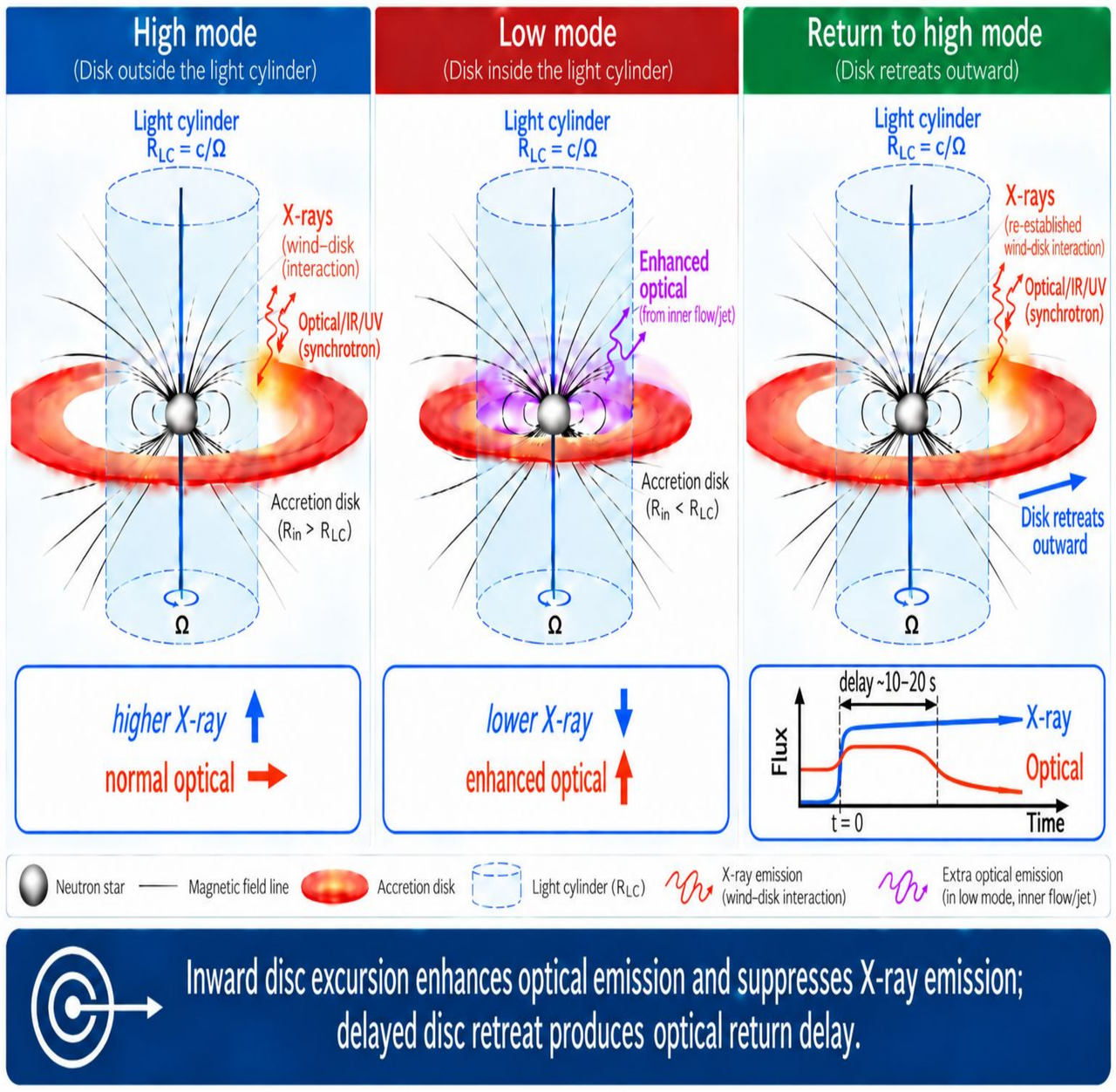


Obs ID	No. low mode	OM Filter			FAP (%)
0724080101	192	U	0.278	0.980	82.59
0800280101	616	White	0.152	1.004	30.02
0923466201	297	V	0.177	1.101	4.08

Optical–X-ray anti-correlation, in which the optical emission increases during X-ray low modes, provides a probe of the coupling between the accretion flow and pulsar magnetosphere. We applied the low-mode analysis developed for PSR J1023+0038 to three simultaneous XMM–Newton observations of 3FGL J1544.6−1125.

None of the three observations reaches our significance criterion, although the anti-correlation becomes stronger toward longer wavelengths. The **V-band observation shows the strongest evidence (FAP = 4.08%)** , suggesting that the longer-wavelength optical emission may be more sensitive to X-ray mode switching.

The X-ray emission responds rapidly to the magnetospheric transition, while the inner disc retreats more gradually, allowing enhanced optical emission to persist after X-ray recovery.



Optical return delay

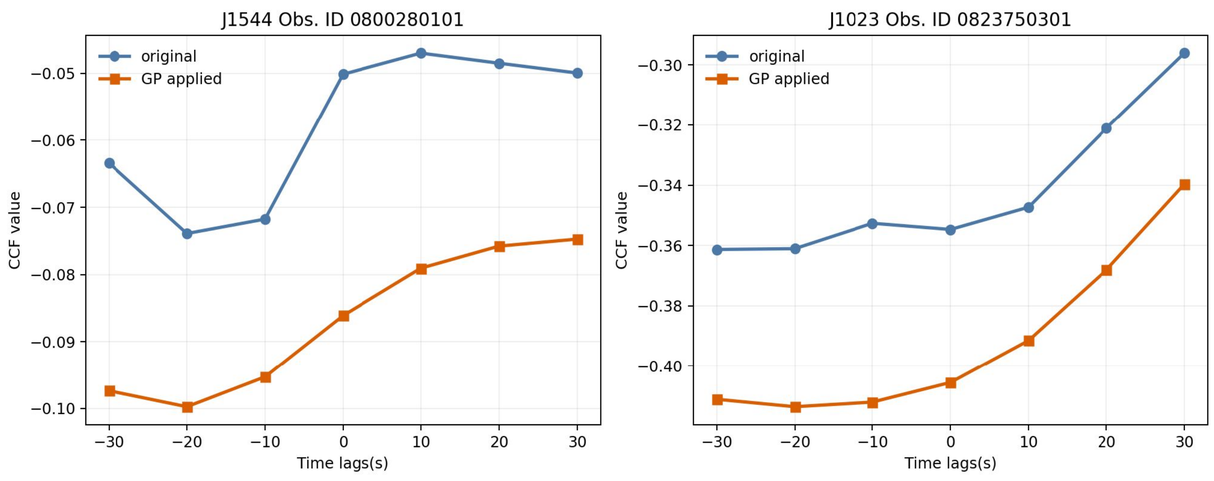
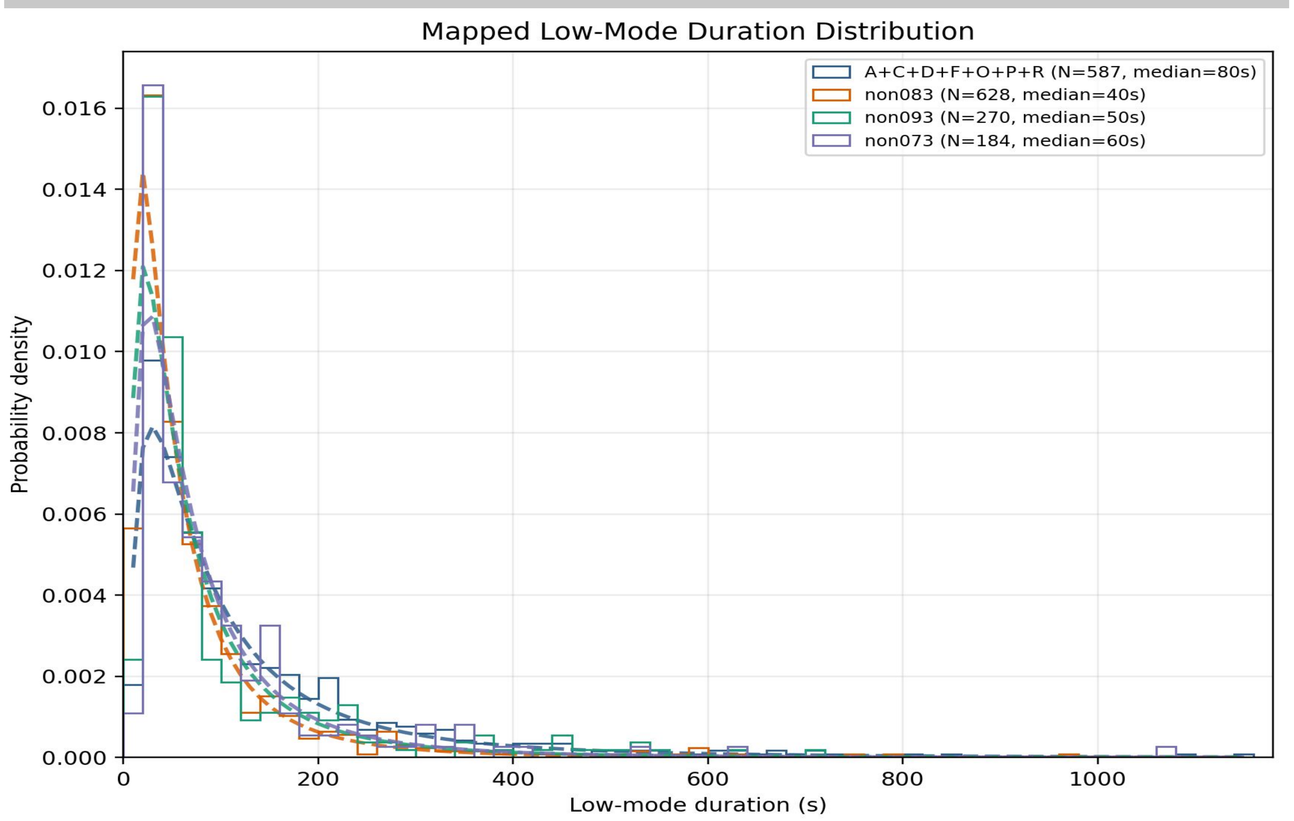


Table 6. Optical return-delay results using $F_{\rm return} = F_{\rm non,opt} + \sigma_{\rm opt}$

Sample	$N_{\rm exit}$	$N_{\rm delay}$	Delayed fraction	Median delay	$p_{\rm binom}$
J1023 significant sample	311	236	75.9%	20 s	7.55×10^{-21}
J1544 Obs. 0724080101	75	29	38.7%	0 s	0.982
J1544 Obs. 0800280101	206	77	37.4%	0 s	0.9999
J1544 Obs. 0923466201	96	36	37.5%	0 s	0.995

The CCF suggests that optical enhancement may persist after the X-ray low mode ends. We measured the delay from each low-to-high transition, defining optical recovery as three consecutive 10-s bins below $F_{return} = F_{non,opt} + \sigma_{opt}$. For J1023, 236/311 transitions (75.9%) show delayed optical recovery, with a median delay of 20 s. In contrast, J1544 shows only 37–39% delayed events and a median delay of 0 s, indicating no clear return-delay signature.

X-ray low mode duration distribution



The X-ray low-mode duration distributions of PSR J1023+0038 and 3FGL J1544.6−1125 are broadly lognormal-like, indicating that short low-mode episodes are common while longer events form an extended tail. However, the typical low-mode duration in J1544 is shorter, with median values of about 40–60 s, compared with approximately 80 s for J1023. This suggests that the mode-switching process in both systems may be governed by similar stochastic mechanisms, but with a shorter characteristic timescale in J1544.