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X-ray and optical orbital modulation of EXO 0748-676: A co-variability study using *XMM-Newton*☆

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HIGHLIGHTS

- A multi-wavelength timing study of the eclipsing LMXB EXO 0748-676 in the hard state.
- Orbital optical and X-ray light curves exhibit large intensity modulations.
- Non-burst X-ray and optical light curves weakly correlated at a few 1000s of seconds.
- Modulations in optical light curves indicate hour-scale evolution of accretion disk.

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ABSTRACT

We present a multi-wavelength timing study of the eclipsing low mass X-ray binary EXO 0748-676 (UY Vol) using *XMM-Newton* when the source was in a hard spectral state. The orbital optical and X-ray light curves show a fairly large amount of intensity modulation in the 7 observations taken during September-November, 2003, covering 36 complete binary orbits of EXO 0748-676. While assessing the non-burst variability, simultaneously in the optical and X-ray light curves, we find that they are not correlated at reprocessing or orbital time-scales, but are weakly correlated at a few 1000s of seconds time-scales. Although a large fraction of the optical emission is likely to be due to reprocessing, the lack of significant correlation and presence of large variability in the orbital X-ray and optical light curves is probably due to structures and structural changes in the accretion disk that produce, and sometimes mask the reprocessed signal in varying amounts. These disk structures could be induced, at least partly, by irradiation. From the observed modulations seen in the optical light curves, there is strong evidence of accretion disk evolution at time scales of a few hours.

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1. Introduction

EXO 0748-676 is a low mass X-ray binary (LMXB) that was discovered with EXOSAT in 1985 (Parmar et al., 1986). Soon after its discovery the optical counterpart was identified as UY Vol (Wade et al., 1985; Pedersen et al., 1985). It is a high inclination ($\sim$ 75–82°) eclipsing binary system with an orbital period of 3.82 h (Parmar et al., 1985; Crampton et al., 1986; Parmar et al., 1986). The presence of thermonuclear bursts in the X-ray light curve established the compact object in the binary as a neutron star (Gottwald et al., 1986; Parmar et al., 1986). Many high and low frequency variabilities have been detected in this source, including a Quasi Periodic Oscillation (QPO) at 695 Hz (Homan and van der Klis, 2000). Galloway et al. (2010) discovered burst oscillations at 552 Hz, which is likely to be the spin period of the neutron star in EXO 0748-676. This object also shows pre-eclipse intensity dips that are commonly understood to be due to obscuration of the central X-ray source by structures in the outer disk, whose azimuthal distribution is variable (Parmar et al., 1986). Mass of the companion has been estimated to be in the range of 0.16 to 0.42 $M_{\odot}$ with the upper limit corresponding to an M2V spectral type star (Hynes and Jones, 2009).

In addition to eclipses, dips and thermonuclear X-ray bursts, this system exhibits a lot of intensity modulation in the X-rays as well as in the UV/optical (Crampton et al., 1986; Parmar et al., 1986; van Paradijs et al., 1988). A significant fraction of the UV/optical emission is understood to be reprocessed emission from the accretion disk (van Paradijs et al., 1988). The broad and shallow eclipses seen in the optical as against the narrow and sharp X-ray eclipses indicate that the reprocessed optical photons are being emitted from an extended region, namely, the accretion disk (Crampton et al., 1986; van Paradijs et al., 1988).

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Table 1
EXO 0748-676 was observed using *XMM-Newton* in 2003. This table details the Obs-IDs, date of observation, number of thermonuclear X-ray bursts, number or reprocessed optical bursts, number of complete orbital segments and non-burst r.m.s variability for the soft X-rays, hard X-rays and optical.

Obs-ID	Date (dd/mm/yyyy)	Start time UT (hh:mm)	t_{exp} (h)	No. of X-ray bursts	No. of Optical bursts	No. of Full orbits	Non-burst soft X-ray variability(%)	Non-burst optical variability(%)	Non-burst hard X-ray variability(%)
0160760101	19/09/2003	13:37	24.6	10	8	6	52.19	13.93	22.68
0160760201	21/09/2003	13:38	25.1	14	13	6	65.25	16.78	25.19
0160760301	23/09/2003	10:42	30.0	14	11	7	50.20	15.38	22.55
0160760401	25/09/2003	17:29	20.4	9	8	5	65.79	17.17	23.16
0160760601	21/10/2003	10:02	15.2	8	6	3	55.82	17.07	22.87
0160760801	25/10/2003	19:19	17.3	9	6	3	73.30	16.11	23.32
01607601301	12/11/2003	08:24	25.2	12	10	6	65.27	19.54	24.97

EXO 0748-676 was moderately bright and displayed a lot of short term variability since the time of its discovery in 1985 till 2008. For a span 24 years, its persistent X-ray luminosity remained at $\sim 10^{36-37}$ ergs/s (Degenaar et al., 2011), after which, it went into quiescence in 2008 (Hynes and Jones, 2009).

Recently, a number of studies involving high inclination neutron star X-ray binaries indicate a correlation between the luminosity state and disk-wind outflows (Ponti et al., 2014). This is similar to the correlation between spectral state and radio jet outflows observed in black hole binaries (Ponti et al., 2012). EXO 0748-676 and AX J1745-281 are two systems in which highly ionized Fe absorption lines (Fe XXV and Fe XXVI) were detected specifically during their soft spectral state (Ponti et al., 2014; 2015). These absorption lines, being indicators of disk-winds, confirmed the fact that a correlation between luminosity state and presence of disk-wind indeed exists (Ponti et al., 2014; 2015). There have also been instances of simultaneous detection of radio-jets as well as disk-wind outflow signatures from objects like GX 13+1, Sco X-1 and GX 340+0, in the hard luminosity state, which indicate that jets and disk-winds may not be mutually exclusive (Homan et al., 2016).

Soon after its discovery, it was observed that EXO 0748-676 displayed different X-ray intensity states (Parmar et al., 1986; Gottwald et al., 1986). Recent studies by Ponti et al. (2014), showed that the bright state displayed less intense dipping phenomenon compared to the faint state. We have also explored this intensity state dependent dipping behavior of EXO 0748-676, in this current work.

Simultaneous X-ray and optical data have been used previously to study the co-variability in LMXBs. Some sources showed X-ray and optical correlation during quiescence (4U 1735-44: Corbet et al., 1989, V404 Cyg: Hynes et al., 2004); some, no correlation during quiescence (Cen X-3: Cackett et al., 2013); others exhibit correlation during highest emission (4U 1556-605: Motch et al., 1989a); while anti-correlated emission (4U 0614+09: Machin et al., 1990) or even bimodal behavior (i.e., correlation as well as anti-correlation, Sco X-1: Ilovaisky et al., 1980) is also seen. The lack of a consistent relation between X-ray and optical variations in LMXBs have usually been interpreted to be due to changes in the extent and visibility of the reprocessing structures that produce most of the optical variability.

The X-ray and optical emission for EXO 0748-676 was initially seen on an average to be correlated on short time scales (Motch et al., 1989b). Thomas et al. (1993) studied the correlated X-ray and optical flux in EXO 0748-676 to understand the reprocessed emission. They did not find any X-ray and optical co-variability that was indicated from earlier studies. Southwell et al. (1996) also confirmed this change in the nature of co-variability. In fact, a larger X-ray flux during the *bright* state would mean an increased mass accretion rate that should make the outer disk bulge more prominent, thereby giving rise to the broad optical eclipse or the optical *high* state. The lack of X-ray and optical co-variability was associated with the geometric masking of the reprocessed emission. Understanding how the system geometry alters the X-ray and reprocessed optical signal requires correlation studies, which we have carried out with very long, simultaneous X-ray and optical light curves, obtained using *XMM-Newton*.

In this paper, we probe the non-burst co-variability of the X-rays and optical emission in this quasi-persistent binary, using *XMM-Newton* observations, when it was in the hard state in 2003. We also present the orbit-to-orbit variations seen in the X-ray and optical light curves.

2. Observations

EXO 0748-676 was observed during September-November, 2003 with *XMM-Newton*. Details of the archival data involving 7 Obs-IDs are shown in Table 1. We have used data from the European Photon Imaging Camera (EPIC) instrument using the PN CCD (0.1–10 keV) for all of the 7 observations. The Optical Monitor (OM, Mason et al., 2001) was simultaneously operated in timing mode using the white band (170–650 nm). EXO 0748-676 was observed for ~600 ks spanning all the 7 Obs-IDs in the X-rays. The EPIC-PN and OM together thus provide a simultaneous multi-wavelength coverage to the target in the X-ray and UV/optical bands.

We reduced the EPIC-PN data using the SAS version 12.0.1 software, using the latest calibration files. The X-ray light curves were extracted in the soft (0.3–5 keV) and hard (5–10 keV) bands from a 40" radius centered on the position of EXO 0748-676 with 1 s binning. The optical light curve was extracted from a region of 6" around the source using the *omichain* task which processes the data with the latest calibration files, and subsequently performs source detection and aperture photometry.

There have been previous burst studies using this dataset by Boirin et al. (2007), spectroscopic studies of the dips by Díaz Trigo et al. (2006), burst spectral studies by Cottam et al. (2008) and a comparison of the optical to X-ray burst emission by Paul et al. (2012). During another observation of EXO 0748-676 with *XMM-Newton* in 2005 (Obs-ID 0212480501), the source was found to be in a soft spectral state (Ponti et al., 2014). We reduced the OM data for this particular dataset as well. However, because of the different filters used and relatively short exposures, the optical light curves from this observation were not suitable for further analysis.

3. Data analysis and results

3.1. X-ray and optical light curves

3.1.1. Raw light curves

The X-ray light curve has been divided into two bands, soft (0.3–5.0 keV) and hard (5.0–10.0 keV). A total of 76 thermonuclear X-ray bursts were reported from all the 7 observations in X-rays (Boirin et al., 2007), a summary of which is presented in Table 1. 63 of these bursts had simultaneous optical band data as well (Paul et al., 2012). There were gaps in the optical data during 13 of the

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