European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME — PERIOD: **80A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title — Category: **D–8**

Bowen-blend echo-tomography of EXO 0748-676 using ULTRASPEC

2. Abstract

We will measure the time delay between the X-ray and optical emission in the X-ray binary EXO 0748-676 in order to measure the inclination and the combined mass of the stellar components in the system. We will employ a new indirect imaging technique which uses the emission from the bowen blend fluorescence mechanism together with *photon-counting spectroscopy* delivered from our custom-built detector system mounted on EFOSC2 to unambiguously determine the time delay from the inner-face of the companion star. This type of observation has never been possible before and could lead the way to similar mass and inclination determinations for all Low Mass X-ray Binaries, parameters which have historically been very difficult to measure via any other method.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	Special3.6	2n	feb	g	n	CLR	v

4. Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:	0	0
b) still required to complete this project:	0	0

5. Special remarks:

6. Principal Investigator: **K. O'Brien** (ESO, ESO, kobrien@eso.org)

CoI(s): V. Dhillon (Sheffield, UK), T. Marsh (Warwick, UK), T. Munoz-Darias (IAC, E), J. Casares (IAC, E)

7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

8. Description of the proposed programme

A) Scientific Rationale:

Accretion plays a key role in many astrophysical systems. It is observed on many size- and time-scales from the power source of AGN and Interacting Binaries to the formation of proto-planetary discs. The proximity and relatively simple geometries of Interacting Binaries make them an ideal accretion laboratories. Some of the best tools we have for studying the structure of such systems and thereby determining many of the binary parameters, which in term constrain physical parameters such as the mass of the compact object in the system, are indirect imaging techniques such as doppler-, eclipse- and echo-mapping.

Echo-mapping

In Low Mass X-Ray Binaries (LMXBs) much of the optical emission arises from reprocessing of X-rays. The optical emission seen by a distant observer is delayed in time of arrival relative to the X-rays due to light travel times of order several seconds between the X-ray source and the reprocessing sites within the binary system. The time-delayed and distorted optical echoes directly measure the locations and sizes of reprocessing sites. By careful analysis of simultaneous optical and X-ray lightcurves, we recover not just the mean time delay, but also *the range of time delays* present between the two. The result of this "deconvolution" is a time-delay transfer function. This transfer function is a 1-dimensional map that resolves the reprocessing sites on the iso-delay surfaces, which are nested paraboloids around the line of sight to the X-ray source (See figure 1). This *echo-mapping* technique has already been developed to interpret AGN lightcurves (Peterson 1993). In AGN the timescale of detectable variations is days to weeks, requiring long observing campaigns, and the resolution we achieve is 1-10 light days (Krolik *et al.* 1991; Horne *et al.* 1991). In LMXBs the size of the system is light seconds rather than light days, and the detectable X-ray and optical variations are correspondingly faster. Our maps of LMXBs will be much better constrained because complete, uniformly sampled lightcurve segments can be readily obtained. (See O'Brien *et al.* 2001 for a review of echo-mapping in LMXBs) *We expect echo mapping to resolve LMXBs with a resolution of order 0.1-1 light seconds or better.*

EXO 0748-676; a rich laboratory

EXO 0748-676 is a persistent X-ray binary that belongs to the sub-class of *bursters* that show frequent type-I thermonuclear bursts from the surface of the compact object, clearly identifying the compact object as a neutron star. The 3.82hr orbital period is well known due to the observation of X-ray eclipses, but the inclination can only be constrained by observational evidence of X-ray eclipses, which set a lower limit of $\sim 75°$ and directly observed X-ray bursts, which set an upper limit of $\sim 82°$.

Bowen-blend echo-mapping; resolving the companion star contribution

In order to determine the time-delay transfer function, we need to study the correlated variability in X-ray and optical lightcurves. This has so-far been measured for a number of different observations. Several simultaneous X-ray/optical bursts have been observed to originate from 4U1636-536 (Pedersen *et al.* 1982, Matsouka *et al.* 1984). But more recently, this effect has been demonstrated in the spectacular results from a large multi-wavelength campaign on the X-ray source EXO 0748-676 (=UY Vol), where simultaneous X-ray/Optical/UV bursts were observed (See Figure 2; Hynes *et al.* 2006), including observations of phase-dependent delays. However, these observations used broadband optical photometry and were therefore relatively insensitive to the location of the reprocessed emission in the binary. This can be seen from the large *range* of delays seen in the time delay transfer function.

In order to remove this uncertainty in the location of the reprocessing region within the binary, Munoz *et al.* (2006) combined the recent discovery that the Bowen-blend emission is centred strongly on the inner face of the secondary. The Bowen-blend are a series of fluorescence lines (mainly CIII and NIII $\lambda 4640$) caused by the intense irradiation. By extracting only the flux from this line, we can unambiguously measure the delay from the secondary star.

By measuring the time-delay transfer function between the X-ray and the optical emission from the secondary (donor) star at two or more orbital phases, we can determine the inclination of the system. The inner face of the secondary moves roughly sinusoidally with binary phase (Figure 3.), so we can constrain the inclination from the ratio of the two delays. Furthermore, the absolute value of the delay, combined with the orbital phase of the observation allows us to strongly constrain the combined masses of the two components in the binary from the orbital separation.

ULTRASPEC; opening a new window on fast spectroscopy

The advent of large optical telescopes, equipped with very efficient spectrographs will enable us to open a new window onto these processes. Instead of relying on sparsely sampled spectroscopy and/or fast broad-band photometry, we can finally study the systems spectroscopically on dynamically important timescales. ULTRASPEC is the first instrument to enable us to do this. The camera we have developed and successfully tested on EFOSC2 in P78, employs an electron-multiplying CCD (EMCCD) to effectively remove the readout noise of the detector whilst maintaining the high QE and large pixel array size of traditional CCDs. This allows us to observe relatively faint targets on sub-second timescales, which is crucial for this work.

B) Immediate Objective: We will obtain spectra of EXO 0748-676 centred around the high-excitation lines of the Bowen Blend ($\lambda 4640$) and He-II ($\lambda 4686$). We will operate ULTRASPEC in 'avalanche' mode, which means

8. Description of the proposed programme (continued)

that we will tag individual photon events with a timescale of $\sim$0.01 seconds and a spectral resolution (R) of $\sim$ 600. This will allow us to extract separate lightcurves of the two lines, which has so-far not been possible with our narrow-band filter used with ULTRACAM (Munoz-Darias *et al.* 2007 and soon to be employed with FORS2 (see P80 proposal by Munoz-Darias). The will also allow us to confirm our hypothesis that the contributions from the two lines originate from the same region (as is seen spectrally from the doppler maps of the system). Additionally, whilst the spectral resolution is sufficient to measure the flux in the line in an individual exposure, it is not enough to sample the dynamical motion of the lines, which is the purpose of a separate proposal by members of this collaboration. Similarly, in that proposal, the FORS1 spectra will not have the time resolution to perform echo-tomography.

Using the EFOSC2 ETC and our knowledge of the ULTRASPEC system, we calculate that we can obtain approximately 20 events above the continuum per second integrated over the emission line. This is enough for our purposes, as we can combine the data from many minutes of observations to create a single transfer function without significant smearing due to the range of phases included. It should be noted that a similar observation on EFOSC2 without our detector would be completely read-noise dominated.

We will use simultaneous X-ray data from RXTE to determine the lightcurve of the source of the irradiation. We have proposed for this time in AO11, the results of which will be known in April 2007. Even if this proposal is unsuccessful, we have a limited amount of time carried over from previous rounds which we can use for these observations.

C) Telescope Justification:

Our system has been specially designed to be used with EFOSC2 on the 3.6m. It is not compatible with other spectrographs.

D) Observing Mode Justification (visitor or service):

This is a visitor instrument and hence the observations must therefore be performed in visitor mode.

E) Strategy for Data Reduction and Analysis:

The data will be reduced using our dedicated pipeline developed specifically for ULTRASPEC. We have many experts in the field of astrotomography, with much experience of similar, albeit slower, observations of this and other sources. We have the necessary computing and manpower resources to analyse and publish this data in a timely fashion.

8. Attachments (Figures)

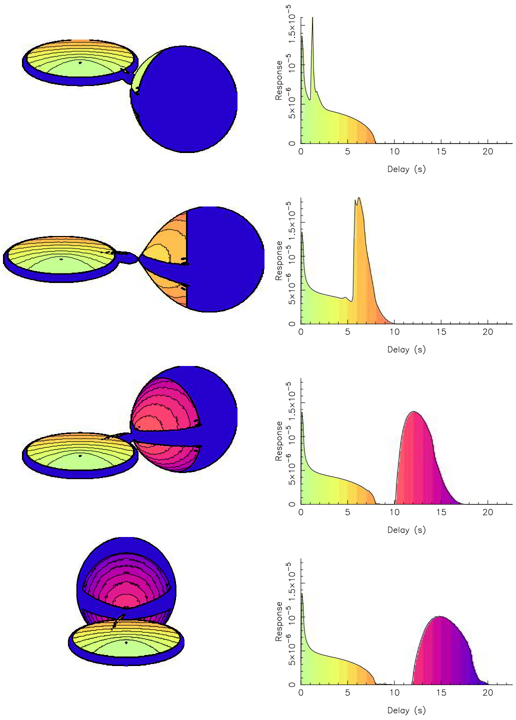

Fig. 1: Sample model time delay transfer functions of an X-ray binary showing the effect of orbital motion on the resulting delays

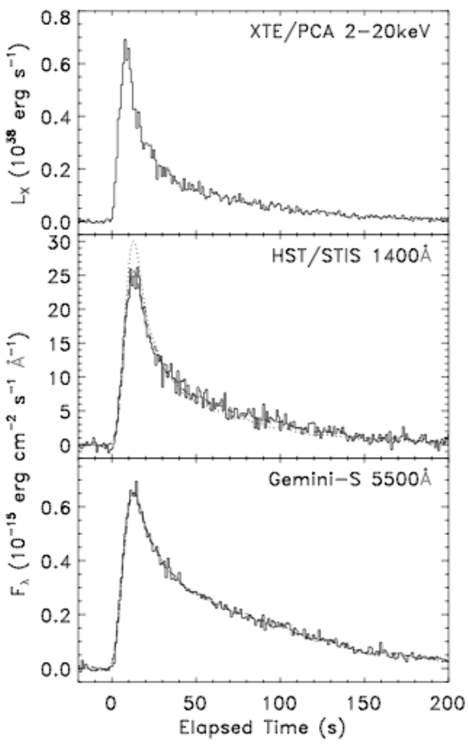

Fig. 2: An example of a type-I X-rtay burst from EXO 0748-676 from Hynes *et al.*, 2006. The X-ray, UV and broadband optical lightcurves can be seen from top to bottom respectively.

8. Attachments (Figures)

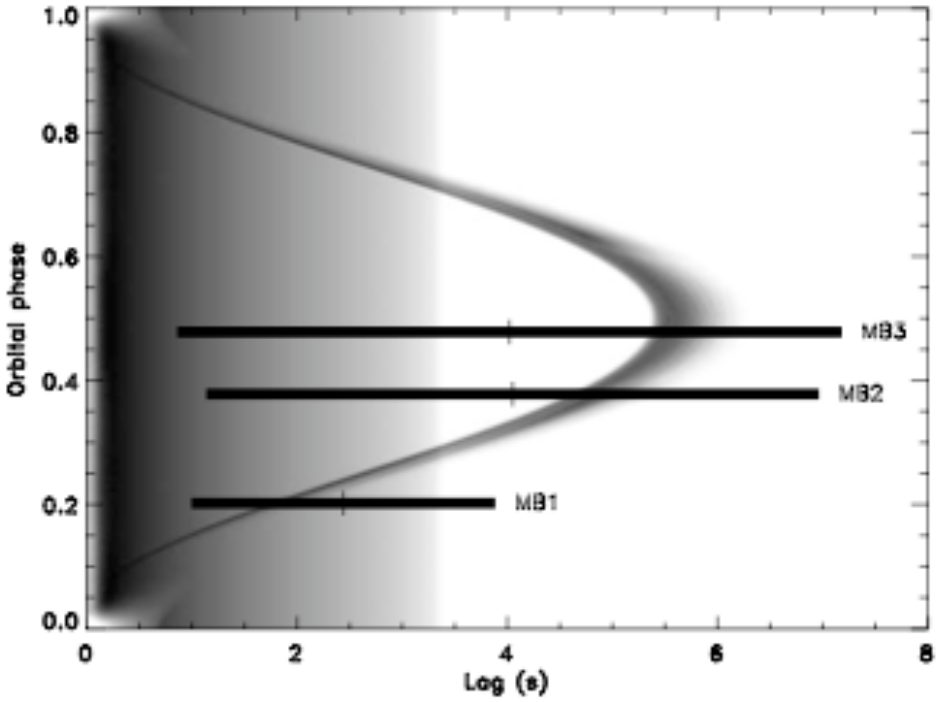

Fig. 3: The orbital phase dependence of the time delay transfer function. The sinusoidal motion of the binary component can clearly be seen to vary from 0 to 5.5seconds. The lines MB1-3 denote the delays from Hynes *et al.*, 2006

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: We would prefer grey time, as the full moon will increase to background making ot more difficult to remove background events from source events and increasing the likelihood of multiple photon events, which will be rejected by the system.

Time Justification: (including seeing overhead) We request 2 nights in order to sample a number of binary orbits to increase the sampling of the transfer functions. This will also increase the likelihood of observing one or more X-ray bursts, which give us a clear 'snapshot' of the system. Additionally, since this is a new instrument, there will inevitably be some optimization of the system necessary which may compromise our science goals if we are granted a single night.
As stated in Section 8(E), we have used the EFOSC ETC to calculate the signal in a 1-sec exposure (which was in good agreement with our observations during the commissioning run). We will use grism 7 and a slit width of 1" to study the line flux from the sources. Since we have zero readout noise in our exposures our S/N will be much higher than is expected from a 'standard' EFOSC2 exposure.

Calibration Request: Standard Calibration

10. Report on the use of ESO facilities during the last 2 years

076.D-0400 - PI Maccarone - 1 night - *Testing Jet Power of Neutron Stars Through High Time Resolution Optical/X-ray Data*, data reduced, publication in preparation
075.D-0494 - PI O'Brien - 1 night - *Coordinated multi-wavelength observations of AE Aqr; FORS-2 HIT-mode spectroscopy*, data reduced, data presented in review proceedings, in press.
075.D-0529 - PI O'Brien - 1 night - *Identifying the infra-red counterparts of INTEGRAL selected sources*, 90% weather loss (seeing > 2" in K-band) data reduced, published in in't Zand *et al.*, 2006, A&A, 448, 1101

11. Applicant's publications related to the subject of this application during the last 2 years

Cornelisse *et al.*, 2007, MNRAS, 375, 1463: A detection of the donor star of Aquila X-1 during its 2004 outburst?
Casares *et al.*, 2006, MNRAS, 373, 1235: Detection of the irradiated donor in the LMXBs 4U 1636-536 (=V801 Ara) and 4U 1735-444 (=V926 Sco)
Pearson *et al.*, 2006, ApJ, 648, 1169: Multiwavelength Observations of EXO 0748-676. II. Emission-Line Behavior
Hynes *et al.*, 2006, ApJ, 648, 1156: Multiwavelength Observations of EXO 0748-676. I. Reprocessing of X-Ray Bursts

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	EXO 0748-676	07 48 33.3	-67 45 00	16.9				

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

No, this is a unique fast spectroscopy mode

13. Scheduling requirements

This proposal involves time-critical observations, or observations to be performed at specific time intervals.

2. Specific date(s) for time critical observations:

Run	from	to	reason
A	11-jan-2008	31-mar-2008	Simultaneous with RXTE, exact schedule TBC

3. Unsuitable period(s) of time

Run	from	to	reason
A	01-oct-07	10-jan-08	ULTRACAM run on WHT means key personnel will not be available until early January

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list

15. Visitor instrument

Description of the instrument and of its operation:

ULTRASPEC is essentially a spectroscopic version of the high-speed, triple-beam imaging photometer ULTRACAM. In combination with the EFOSC2 spectrograph on the ESO 3.6m telescope, ULTRASPEC provides high speed (up to $\sim$100 Hz) spectroscopy with zero readout noise. It achieves this by using an E2V CCD201 detector mounted in a standard ESO cryostat and the ULTRACAM data acquisition hardware/software. The CCD201 is a so-called *electron-multiplying* CCD (or EMCCD). This is a frame-transfer device (hence providing high speed and negligible dead-time) with an extended serial register to which a higher-than-usual voltage is applied. Secondary electrons are produced as the photon-generated electrons are clocked through it, resulting in a signal amplification which dwarfs the readout noise, rendering it negligible. In all other respects, the CCD201 is similar to a conventional CCD detector, with an area of 1024x1024 pixels^2 (each of 13 microns), a peak quantum efficiency of over 90% and very low dark current.

As reported in a forthcoming ESO Messenger article (see http://www.shef.ac.uk/physics/people/vdhillon/ultraspec/ultraspec_messenger.html), ULTRASPEC has the potential to revolutionise readout-noise limited spectroscopy. During our commissioning run (see below), for example, we effectively turned the ESO 3.6-m telescope into a 6.3-m telescope, purely due to the elimination of readout noise. The improvement is even greater if one takes into account the greater efficiency of ULTRASPEC provided by the essentially zero dead-time between exposures.

On which telescope(s) has your instrument been commissioned and/or used (scientific publications): Four nights of technical time were awarded by the Director of La Silla-Paranal Observatory to commission ULTRASPEC on EFOSC2 and to perform an on-sky evaluation of EMCCDs for astronomical spectroscopy. The run took place on 2006 December 1–4 and was a great success. We would now like to use ULTRASPEC to do science. This proposal is one of several being submitted to the OPC for period 80. If successful, we request that the OPC schedules it together with any other successful ULTRASPEC proposals in a single block of time early in 2008.

Total weight and value of equipment to be shipped: Total weight of ULTRASPEC and its ancillary equipment, including the 3 packing crates: 450 kg. Approximate value of equipment: 300 000 Euros.

Weight at the focus (including ancillary equipment): The ULTRASPEC (ESO) cryostat weighs approximately 30 kg when full with liquid Nitrogen. The SDSU CCD controller weighs approximately 10 kg. The ULTRASPEC electronics rack weighs approximately 100 kg. The resulting total is well within limits and did not cause any problems with telescope balance, pointing, tracking or guiding during the commissioning run.

Compatibility of attachment interface with required telescope focus: The cryostat used by ULTRASPEC is a standard ESO unit which has been used in the past on EFOSC2. Hence there are no compatibility issues. The SDSU CCD controller mounts on an ESO-supplied frame at the bottom of EFOSC2, and the ULTRASPEC electronics rack sits on a free bay in the Cassegrain cage using an ESO-supplied mounting plate. The cables between the rack and cryostat run through a hole in the centre of the floor of the Cassegrain cage, which acts as a simple cable twister. Photographs of the mounting arrangement can be seen in the commissioning report we submitted to ESO in January 2007:
http://www.shef.ac.uk/physics/people/vdhillon/ultraspec/eso_comm_report.html.

Back focal distance value: The EFOSC2 spectrograph requires the EMCCD used in ULTRASPEC to lie 14.0$\pm$0.5mm from the mounting flange of the ESO cryostat in which it is installed. Furthermore, the CCD must be flat to approximately 100μm with respect to this flange. These adjustments were made in the lab using a travelling microscope prior to commissioning and the resulting alignment proved excellent during on-sky tests in December 2006 (see the report on the commissioning run).

Acquisition, focusing, and guiding procedure: Due its high-speed readout, ULTRASPEC can operate with its full 2.4 arcminute field in a "TV acquisition mode", so acquiring targets and focusing is straight-forward using EFOSC2's imaging mode. Autoguiding is provided by an independent Cassegrain autoguider. More details are given in the report on the commissioning run.

Compatibility with ESO software standards (data handling): ULTRASPEC's system architecture closely follows the ESO model: the instrument has a Local Control Unit (LCU; a rack-mounted, dual-processor linux PC located next to the cryostat in the Cassegrain cage) which can be controlled over the ESO 3.6m LAN by any workstation that is able to open an xwindows session on it. There is no interface with the TCS/ICS, so the telescope, EFOSC2 and ULTRASPEC all run in a stand-alone mode. Further details are given in the commissioning plan we submitted to ESO in October 2006: http://www.shef.ac.uk/physics/people/vdhillon/ultraspec/commissioning.html.

Estimate of supplies and services expected from ESO (in person days): Having already had a successful commissioning run in period 78 on the ESO 3.6m, ESO technical support in period 80 will be limited to assistance with mounting and dismounting the cryostat, CCD controller and electronics rack at Cassegrain, and connecting our computer facilities to the ESO 3.6-m LAN. Further details are given in the commissioning plan.