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**

Understanding dwarf nova oscillations

2. Abstract

Semi-coherent oscillations seem to be a hallmark feature of accretion onto compact objects, from neutron stars and white dwarfs up to the black holes within X-ray binaries. In the white dwarf binaries, these modulations are known as dwarf nova oscillations (DNOs). DNOs probe the very inner regions of the accretion flow in cataclysmic variables, but have no accepted theory to explain them, despite being a well-known phenomena for over 20 years.

We propose high time resolution spectroscopy using ULTRASPEC/EFOSC2 as a test of competing models of DNOs. By using the velocity information added by spectroscopy, we aim to establish the physical location of the DNOs. This will decide unambiguously between competing DNO models, and establish if the phenomena seen in accretion onto white dwarfs, neutron stars and black holes can be physically linked.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	Special3.6	2n	Feb	n	$\leq 1.0''$	THN	v

4. Number of nights/hours

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

5. Special remarks:

We propose to use Ultraspec, which is offered on a shared-risk, collaborative basis with Vik Dhillon (University of Sheffield) and Tom Marsh (University of Warwick).

6. Principal Investigator: S. Littlefair

(Sheffield, UK, s.littlefair@shef.ac.uk)

CoI(s): V. Dhillon (Sheffield, UK), T. Marsh (Warwick, UK)

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:

Dwarf nova oscillations (DNOs) are rapid (8–40s) modulations with rich and varied phenomenology. They are seen in the light of accreting white dwarf binaries with high mass transfer rates (dwarf novae in outburst and nova-like variables). Typically they are low-Q modulations; their periods can change by seconds on timescales of hours, or be stable to milliseconds for many hours, giving $10^3 < Q < 10^7$ - see figure 1 for an example of DNOs. Often multiple frequencies are present in a 1:2:3 ratio (Warner & Woudt 2005, ASPC, 330, 227), and there is a monotonic relationship between the period of modulation and the EUV flux, which is a good measure of accretion rate in these systems (Warner 2004, PASP, 116, 115). Despite the discovery of DNOs in the very early days of rapid photometry of CVs (Warner & Robinson 1972, Nature, 239, 2), there is still no accepted explanation for how DNOs are excited or sustained for long periods.

Because the observed frequencies in DNOs obey the same scaling laws as seen in the kHz quasi-periodic oscillations (QPOs) of low-mass X-ray binaries (which contain neutron star or black hole primaries), it has been argued that they represent the same phenomenon (Mauche 2002, ApJ, 580, 423). The kHz QPOs have received much interest as they are though to represent the dynamics of matter in strong-field gravity. The link between DNOs and QPOs however, argues that models invoking strong gravity to explain the kHz QPOs cannot be correct, and raises the possibility of studying the QPO phenomenon without using expensive X-ray observing time.

Possible explanations for the DNO/QPO phenomenon are diverse, including: relativistic precession models; pulsations or precession of a layer on the compact object's surface (Piro & Bildsten 2004, ApJ, 616. 155; Warner & Woudt 2005); radial and vertical oscillations of the disc (Kluzniak & Abramowicz 2003, astro-ph/0304345) and the resonant response of the disc to periodic perturbations from the magnetic field of the compact object (Kluzniak et al 2005, A&A, 440, 25). Since some of these theories depend upon the compact object possessing either a surface or magnetosphere, or upon strong gravity, they are clearly not compatible with a common explanation for DNOs and QPOs.

It is embarassing that such a widespread phenomenon is still unexplained. A major part of the problem is that current observations of DNOs and QPOs do not provide stringent observational tests of the existing models. Rapid photometry has provided information about the periods present and the relationships between them, as well as the coherence and dependence of the oscillations on mass transfer rate through the disc. Unfortunately, this has not been sufficient to discriminate between various models. We can overcome these problems by obtaining time-resolved spectroscopy of DNOs; the velocity information gained from studying DNOs in the emission lines allows the physical location of the DNOs to be determined, immediately choosing between models in which the oscillation is located on the surface of the star (Piro & Bildsten 2004; Warner & Woudt 2005b), or in the accretion disc (Kluzniak et al 2005). Until now, this spectroscopy was not practical, as it requires spectroscopy with frame rates around 1 Hz, something that is rendered impossible by the long dead-times necessary to read out a spectroscopic CCD, and the detrimental impact of read noise.

To overcome both these problems, we have recently designed, constructed and commissioned ULTRASPEC. It is a private instrument, based upon its imaging counterpart, ULTRACAM. ULTRASPEC is designed to use the external focus of EFOSC2, and was succesfully commissioned in December 2006. ULTRASPEC uses frame-transfer devices in order to obtain frame rates up to hundreds of Hertz, with negligible dead-time. At the heart of ULTRASPEC is an electron-multiplying CCD (EMCCD). These are conventional CCDs, but 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. We propose using ULTRASPEC with EFOSC2 to obtain rapid, high signal-noise ratio spectroscopy of dwarf novae in outburst. This will allow us to determine the spatial location of the DNOs, and thus decide between competing models of DNO formation.

B) Immediate Objective:

The power of time-resolved spectroscopy to explain DNOs is shown by the results of Steeghs et al (2001, MNRAS, 323, 484). Using their own novel data acquisition system in combination with LRIS/KECK they bypassed the dead-time problem (though not the read-noise issue) and obtained very fast (72 ms) spectroscopy of the dwarf nova V2051 Oph on decline from outburst (see figure 2). They detected coherent oscillations in both the continuum and the emission lines. By folding the data upon the oscillation period they were able to show that the emission line oscillation was located in the accretion disc, at a radius roughly co-incident with the circularisation radius for this system (see figure 3). These results immediately suggest that the DNOs are located in the accretion disc, but more information is needed before we can determine what mechanism excites DNOs. Are all DNOs located in the disc? Is the spatial location of all frequencies the same, as predicted by the disc perturbation model of Kluzniak et al 2005? Is the spatial location of DNOs always consistent with the

8. Description of the proposed programme (continued)

circularisation radius, implying that DNOs are excited by the interaction of the gas stream from the donor with the accretion disc (Steeghs et al 2001)?

To address these questions we will extend the methodology of Steeghs et al (2001) to two more dwarf novae in outburst. To do so we will require spectroscopy with frame rates of 1Hz or higher. We will use ULTRASPEC with a specially commissioned VPH-based grism. The grism will provide a spectral resolution of ∼3Å in seeing of 1″, and will cover the strong emission lines of Hα and He I (λ6678) together with sufficient continuum for us to compare the DNOs in the continuum and line emission. Since there is no read noise, we can run at frame rates of 10Hz, and bin our data temporally at the analysis stage to achieve the time resolution we require. ULTRASPEC can provide frame rates of 10Hz with minimal dead time, making this a highly efficient observing strategy. The absence of read noise means that we will obtain a signal-noise ratio of ∼11 *in one second* on a typical, V=14, target (compared to a signal-noise ratio of ∼5 with EFOSC2). Provided we average two orbits together, the unique capabilities of ULTRASPEC ensure the data obtained will closely match the signal-noise ratio obtained by Steeghs et al (2001), despite having higher spectral resolution, and being taken on a much smaller telescope. It will therefore be of sufficient quality to allow us to achieve our scientific goals.

We will follow a similar analysis to Steeghs et al (2001), and determine the physical location of each DNO frequency we detect. We will use these results to determine if the DNOs are located in the disc for all dwarf novae. If so, does the radius of the DNOs always correspond to the circularisation radius? We will also determine if the multiple DNO frequencies, often observed in a 1:2:3 ratio, arise from the same spatial location. This information will be used to test the existing models of DNO formation, and to determine if their driving mechanism is compatible with a consistent explanation for the quasi-periodic oscillations seen in accretion onto *all* compact objects.

C) Telescope Justification: This proposal is made possible by the unique capabilities of ULTRASPEC. Since ULTRASPEC is designed to use the EFOSC2 optics, it goes without saying that the ESO 3.6m telescope is the only telescope worldwide on which this data can be taken.

D) Observing Mode Justification (visitor or service): ULTRASPEC is a specially designed visitor instrument requiring the presence of a dedicated team. We therefore request visitor status.

E) Strategy for Data Reduction and Analysis: Data reduction and analysis packages for ULTRASPEC data have been created by our team. Analysis will be undertaken by Littlefair, who will dedicate 100% of his time to this project. We estimate three man-months for the production of a paper.

8. Attachments (Figures)

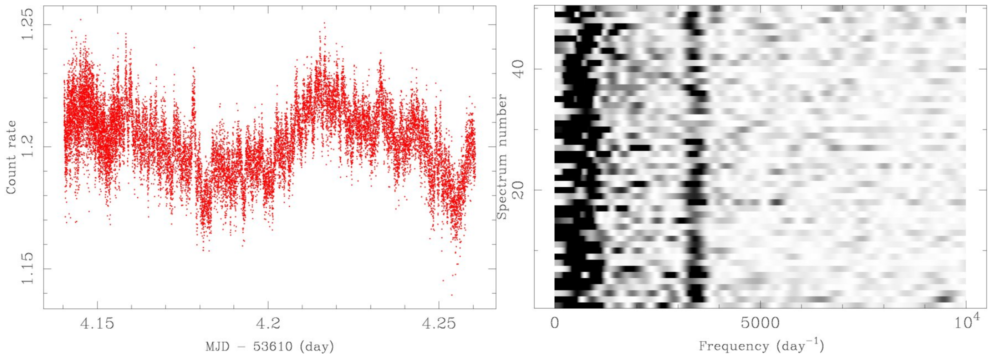

Fig. 1: Left panel - ULTRACAM+WHT lightcurves of the dwarf nova KT Per, taken a few days after outburst at a magnitude of $g' \sim 14$. Lots of low frequency noise (flickering) is visible. Right panel - a trail of Lomb-Scargle periodograms from the same lightcurve. The DNO is clearly visible at 3500 cycles per day.

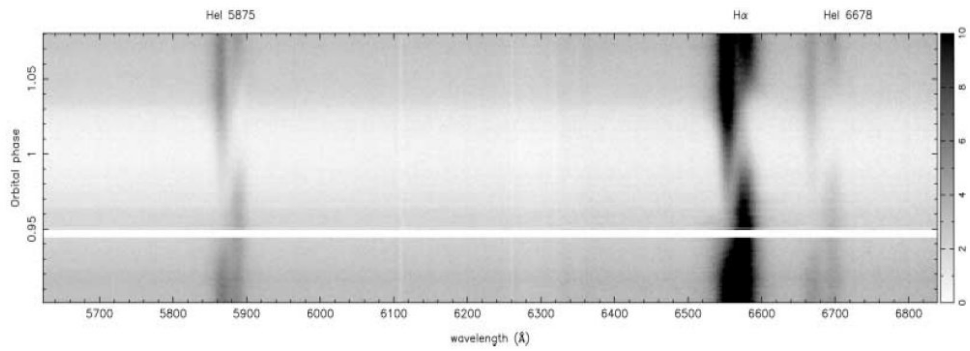

Fig. 2: Trailed spectrogram of the dwarf nova V2051 Oph, taken from Steeghs et al (2001). Gray scale denotes flux in mJy. Gaps occur at times of background measurements.

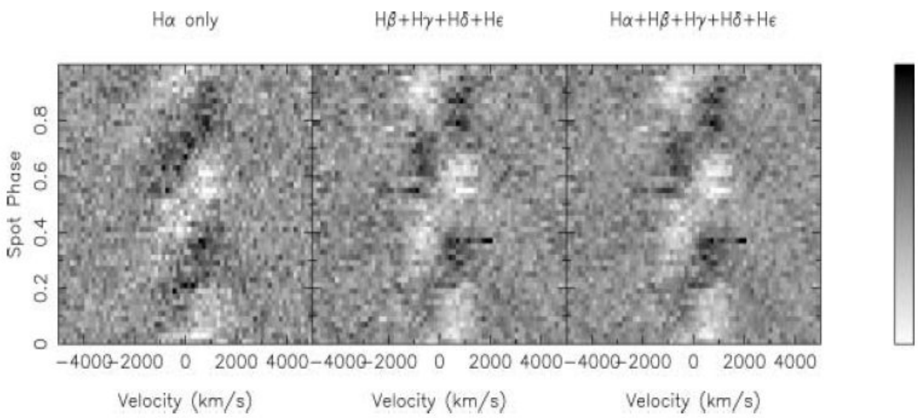

Fig. 3: The emission lines in V2051 Oph folded on an oscillation period of 59.5 seconds, and with a running mean filter applied to subtract the non-oscillating background. All Balmer lines show identical kinematics. These kinematics were used to show that the DNOs were consistent with a spatial location within a disc bulge in Keplerian rotation at the circularisation radius (Steeghs et al 2001).

9. Justification of requested observing time and lunar phase

Lunar Phase Justification:

At V∼ 14, frame rates of 1s, and a resolution of ∼3Å, the dominant source of noise with a conventional CCD would be read noise. With ULTRASPEC we are dominated by shot noise from the object regardless of lunar phase, and thus we have no lunar phase restriction.

Time Justification: (including seeing overhead)

The "Immediate Objective" section outlines that we will obtain a signal-noise of ∼11 on our targets in one second. Our aim of using line kinematics to infer the spatial location of oscillations means we must observe the binary for at least one complete orbital cycle. Observing for two orbital cycles ensures our data will match the signal/noise ratio of Steeghs et al (2001), with the added of advantage that averaging two orbits will reduce the stochastic variability (flickering), seen in figure 1. Observing two orbits of each target will thus ensure the data is of sufficient quality to meet our aims.

We require observations of two dwarf novae in outburst. Typical periods of dwarf novae are ∼ 4 hours, and we request 8 hours per target to cover two full orbits for each dwarf novae. Our total time request is thus 16 hours, or two nights.

Calibration Request: Standard Calibration

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

075.C-0419(A) "Are young stars spun down by their discs?" - Data reduced and analysed. Results presented at Protostars & Planets V. Paper in prep.

075.C-0505(A) " Ultra-cool dwarfs with ULTRACAM: On the causes of variability." Data published as Littlefair et al, MNRAS, 370, 1208, 2006.

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

Barros, S., et al, 2007, MNRAS, 374, 1334: ULTRACAM photometry of the ultracompact binaries V407 Vul and HM Cnc

Gaensicke, B, et al, 2006, Science, 314, 1908: A Gaseous Metal Disk Around a White Dwarf

Littlefair, S., et al, 2006, Science, 314, 1578: A Brown Dwarf Mass Donor in an Accreting Binary

Burleigh, M., et al, 2006, MNRAS, 373, 1416: The nature of the close magnetic white dwarf + probable brown dwarf binary SDSSJ121209.31+013627.7

Southworth, J., et al, 2006, MNRAS, 373, 687: VLT/FORS spectroscopy of faint cataclysmic variables discovered by the Sloan Digital Sky Survey

Littlefair, S., et al, 2006, MNRAS, 371, 1435: ULTRACAM observations of SDSS J170213.26 + 322954.1 - an eclipsing cataclysmic variable in the period gap

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	A dwarf nova	0 – 13 hrs	less than 15	8.0	~14			
A	A 2^{nd} dwarf nova	0 – 13 hrs	less than 15	8.0	~14			

Target Notes: The targets will be chosen from a list of dwarf novae in outburst at the time of observations. This list will be provided by amateur astronomers. At any given time there are ~10 such objects observable.

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.

This project requires very high time resolution spectroscopy. No suitable data are in the archive.

13. Scheduling requirements

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

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.