**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

VISITING ASTRONOMERS DEPARTMENT • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: visas@eso.org • Tel. : +49-89-32 00 64 73

# 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–5**

High-speed optical spectroscopy of the Vela pulsar

2. Abstract

Optical spectroscopy of pulsars plays a crucial role in determining the relative importance of magnetospheric emission and thermal emission from pulsars. *Spin phase resolved* spectroscopy can further determine properties of the magnetospheric emission, determining properties like the phase dependence of the electron population, and the presence of local beaming. Phase resolved spectroscopy has only been possible to date for the Crab pulsar, severely limiting our knowledge of the emission from pulsars, and making any study of the evolution of optical emission impractical.
We propose using the novel instrument ULTRASPEC to overcome the limitations of conventional CCDs, and obtain phase resolved spectrscopy of the Vela pulsar.

3.

| Run | Period | Instrument | Time | Month | Moon | Seeing | Sky Trans. | Obs.Mode |
|---|---|---|---|---|---|---|---|---|
| A | 80 | Special3.6 | 4n | feb | d | $\leq 1.0''$ | PHO | v |

| 4. 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:

This is one of a number of proposals to make use of the high-speed, zero readout-noise camera ULTRASPEC, which was commissioned on the EFOSC2 spectrograph of the ESO 3.6m telescope in December 2006.

6. Principal Investigator: **V. Dhillon** (University of Sheffield, UK, vik.dhillon@shef.ac.uk)

CoI(s): T. Marsh (University of Warwick, UK), S. Littlefair (University of Sheffield, UK), A. Shearer (NUI, Galway, OTHER), P. Kerry (University of Sheffield, UK), C. Copperwheat (University of 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:

The Vela pulsar is believed to be approximately 10 000 years old, making it a transition object between the young pulsars ($\sim$1000 years), such as the Crab, and the middle-aged pulsars ($>$100 000 years), such as Geminga. The Vela pulsar was the second pulsar after the Crab to be detected optically (Lasker 1976); at a magnitude of V=23.6, Vela is currently the third brightest optical pulsar, and it is known to exhibit optical pulsations on the radio period of 89 milliseconds (Wallace 1977).

As pulsars age, it is believed that the magnetospheric emission responsible for the optical light becomes weaker, while the thermal component becomes more significant and eventually dominates (van Kerkwijk & Kulkarni 2001). The soft X-rays appear to behave in a similar manner. In keeping with its status as a transition object, Vela's optical emission is totally pulsed (and magnetospheric in origin) whereas it is a thermal soft X-ray emitter. This change in emission properties must represent an evolution of the underlying emission mechanisms, but what this evolution is, and what drives it, is highly uncertain.

In order to understand the emission mechanism of pulsars like Vela, and hence to understand how the emission of pulsars evolve as they age, it is important to characterise their optical spectra. For example, the spectral slope, evidence for spectral features, and (crucially) the way both of these vary with spin phase can all be used to challenge models of pulsar emission (e.g. Romani et al. 2001). As an intermediate age object, Vela is ideally placed to study the evolution of the emission mechanism between Crab-like pulsars and Geminga-like pulsars.

Spectroscopy of pulsars is a challenging task, however, due to their extreme faintness and short spin periods. Even the Crab pulsar, by far the brightest optical pulsar at V=16.6, has been subjected to only a few phase-resolved spectroscopic studies (see Fordham et al. 2002 and references therein) and Vela has never been the subject of such a study. With our knowledge of the optical spectra of pulsars based almost entirely on the Crab, the field is in an analagous state to the field of solar system studies before the discovery of extra-solar planets. It is vital to try and extend these studies to other pulsars. Vela is relatively bright, and has a long spin period, making it an ideal target.

All that is known of the optical spectrum of Vela comes from the multi-colour photometric studies by Mignani & Caraveo (2001) and Nasuti (1997), and neither of these were phase-resolved. Nasuti (1997) presented UBVR magnitudes consistent with a magnetospheric origin, but with a substantially different spectral shape compared to that of the Crab and Geminga due to an apparent turnover around 6000Å. Mignani & Caraveo (2001) extended this study to the red, and found marginal evidence for a dip around 6500Åwhich remains to be confirmed. Since the Crab spectrum is an unbroken power law (the spectral index depends upon spin phase), the presence of spectral features in Vela would represent the emergence of thermal emission from underneath the magnetosphere, confirming the ideas of van Kerkwijk & Kulkarni (2001).

We propose phase resolved spectroscopy of the Vela pulsar. This spectroscopy will provide a crucial observational picture of how the magnetospheric emission from pulsars declines with age. The spectral shape, and its dependence on spin phase will be used to give unique observations of the optical emission mechanisms in intermediate age pulsars, and determine if the optical properties are consistent with the gradual emergence of thermal emission.

**References**

Fordham et al, 2002, ApJ, 581, 485
Lasker, 1976, ApJ, 203, 193
Mignani, Caraveo, 2001, A&A, 376, 213
Nasuti et al, 1997, A&A, 323, 839
Romani et al, 2001, ApJ, 563, 221
van Kerkwijk, Kulkarni, 2001, A&A, 378, 986
Wallace et al, 1977, Nature, 266, 692

B) Immediate Objective:

With the advent of ULTRASPEC on the EFOSC2 spectrograph of the ESO 3.6m telescope, we now have a facility which offers the possibility of obtaining phase-resolved optical spectroscopy of pulsars other than the Crab. Rapid spectroscopy with conventional CCDs is rendered impractical by the long dead-times necessary to read out a spectroscopic CCD, and the detrimental impact of read noise. ULTRASPEC was designed, constructed and commisssioned to overcome both these problems. ULTRASPEC uses frame-transfer devices in

## 8. Description of the proposed programme (continued)

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 will use ULTRASPEC in photon-counting mode, with exposure times of 18ms. We will use EFOSC2 Gr#1, giving a spectral coverage of approximately 5000–8500Å at a spectral resolution of approximately 36Å. Using a 1024x100 pixel window, with 2x2 binning and fast readout mode it will take 170ms to read out a frame. Many frames will be phase folded and binned into 5 phase bins using a spin period from the Parkes radio observatory. The resulting, phase resolved will be binned into 200 resolution elements (optimally sampling the 36Å resolution above) to give final spectra with a signal-noise of ∼14 (see Time Justification for details). These spectra will represent a massive leap forward in our knowledge of Vela's optical emission; not only will it be the first phase resolved spectral information, but each of the 200 resolution elements, *in each phase bin* will possess a similar signal-noise ratio to the existing photometric measurements.

We will use this data to confirm the reality of the 6500Å dip seen by Mignani & Caraveo (2001). If confirmed, this will provide observational confirmation that pulsars gradually reveal thermal emission as they age. We will also use our date to look for changes in the spectral index in Vela's spectrum as a function of spin phase. By comparison with emission models, we can use this property to constrain the synchroton emission properties, such as the electron power law, $s$, the pitch angle of electron components, and the possible importance of local beaming of the radiation cones (see Romani et al 2001, for example). ULTRASPEC has made this possible for the first time in any pulsar, other than the Crab.

### C) Telescope Justification:

The short spin period of the Vela pulsar demands a high-speed camera. It also requires as large an aperture telescope as possible, combined with an efficient spectrograph, in order to collect as many photons as possible during the brief exposures. ULTRASPEC on the EFOSC2 spectrograph of the ESO 3.6m telescope is hence the ideal combination for such a study. Note also that the Vela pulsar is a southern target, and hence much better observed from La Silla than from a 4m-class telescope in the northern hemisphere.

### D) Observing Mode Justification (visitor or service):

ULTRASPEC is a private instrument operated by the Universities of Sheffield and Warwick, in collaboration with staff at the UKATC and ESO. Hence it must be operated by the ULTRASPEC team in visitor mode.

### E) Strategy for Data Reduction and Analysis:

We have developed a pipeline data reduction system for ULTRASPEC, modelled on the successful ULTRACAM data reduction pipeline. The pipeline allows us to view spectra (and trailed spectra) in real time, both in photon-counting and non-photon counting modes. The same data reduction system will then be used when we are back at our home institutions to perform a full and final reduction of the data.

We will request an up-to-date value of the spin period of the Vela pulsar from the Parkes radio observatory at the time of observation. The ULTRASPEC data will then be folded on this period and binned into 5 phase bins. The spectra will then be rebinned in the dispersion direction into 200 resolution bins, giving 5 phased resolved spectra, each with a signal-noise ratio ∼14. Data reduction and analysis will be shared between Dhillon, Littlefair and Shearer

## 8. Attachments (Figures)

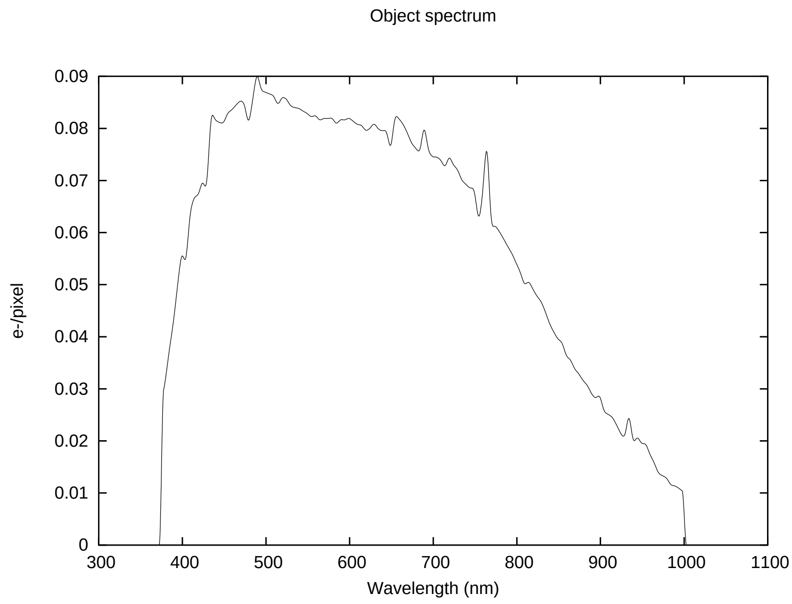


Fig. 1: Object counts from the EFOSC2 exposure time calculator. The exposure time has been scaled by a factor of 100 in order to avoid rounding errors in the ETC.

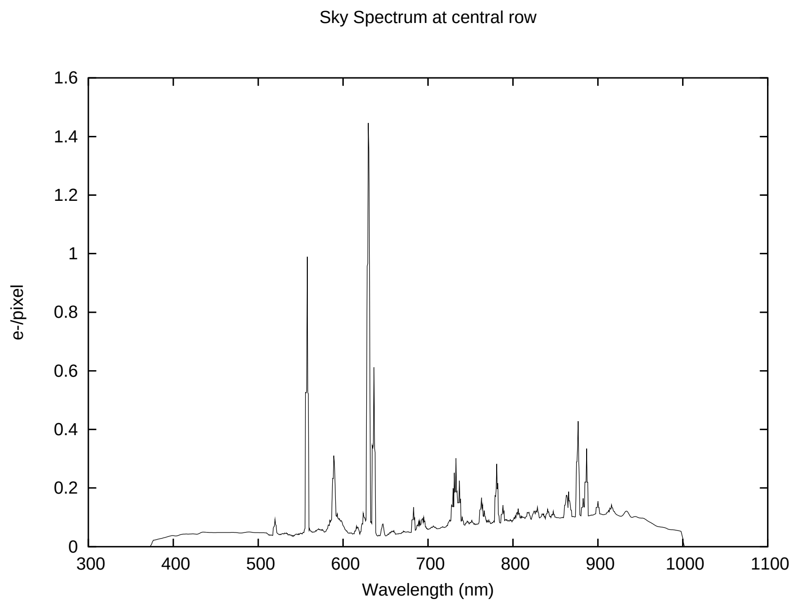


Fig. 2: Sky counts from the EFOSC2 exposure time calculator. The exposure time has been scaled by a factor of 100 in order to avoid rounding errors in the ETC.

## 9. Justification of requested observing time and lunar phase

**Lunar Phase Justification:** Dark time is essential due to the extreme faintness of the target and the fact that, since we are not readout-noise limited with ULTRASPEC, minimising the sky brightness has a much larger impact on the resulting signal-to-noise than with a conventional CCD.

**Time Justification: (including seeing overhead)**
We require spectroscopy of the vela pulsar with a useable signal-noise ratio, temporally resolved into five spin phase bins. This would be impossible with a conventional CCD, whereas it is merely difficult with ULTRASPEC!

Resolving 5 phase bins sets our maximum exposure time to 18ms. In a single 18ms exposure we will obtain peak object counts of 0.0009e- (see fig 1) and average sky counts of 0.0015 e-/pixel. With no read noise, a single exposure gives a signal/noise per resolution element of 0.04. Reading out a frame introduces a deadtime of 170ms, so each exposure takes 188ms. In 32 hours (4 nights) we can average $\sim$123,000 frames into each phase bin, giving a signal-noise ratio in each phase bin of $\sim$14. Our total time request is 4 nights.

**Calibration Request:** Standard Calibration

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

075.C-0786: *The masses and radii of extrasolar planets.*
Time was awarded in May 2005 with ULTRACAM to observe 3 of the transiting extrasolar planets discovered by OGLE (56b, 113b, 132b). The data, which suffered from relatively poor observing conditions and crowded fields, have now been reduced and are currently being analysed with a transit light-curve fitting code that we have just completed writing.

075.C-0493: *A search for optical pulsations in the AXPs 1E 1048.1−5937 and 1RXS J1708−4009.*
Time was awarded in May 2005 to observe just 1E 1048.1−5937 with ULTRACAM. The data have been reduced and analysed. Unfortunately, due to relatively poor seeing, and the fact that 1E 1048.1−5937 was in a relatively faint state, we were only able to detect the object at $3\sigma$ by averaging all the frames, rendering a study of the optical pulses impossible.

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


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

Littlefair S., Dhillon V., Marsh T. et al., 2006, Science, 314, 1578: A Brown Dwarf Mass Donor in an Accreting Binary *(based on ULTRACAM data)*

Dhillon V., Marsh T., Littlefair S., 2006, MNRAS, 372, 209: A search for optical bursts from the rotating radio transient J1819−1458 with ULTRACAM

Littlefair S., Dhillon V., Marsh T., Gänsicke B., 2006, MNRAS, 371, 1435: ULTRACAM observations of SDSS J170213.26+322954.1 – an eclipsing cataclysmic variable in the period gap

Mathioudakis M., Bloomfield D., Jess D., Dhillon V., Marsh T., 2006, A&A, 456, 323: The periodic variations of a white-light flare observed with ULTRACAM

Littlefair S., Dhillon V., Marsh T. et al., 2006, MNRAS, 370, 1208: Observations of ultracool dwarfs with ULTRACAM on the VLT: a search for weather

Roques F. et al., 2006, AJ, 132, 819: Exploration of the Kuiper Belt by High-Precision Photometric Stellar Occultations: First Results *(based on ULTRACAM data)*

Aerts C., Jeffery C., Fontaine G., Dhillon V., Marsh T., Groot P., 2006, MNRAS, 367, 1317: High-speed colourimetry of the subdwarf B star SDSSJ171722.08+58055.8 with ULTRACAM

Brinkworth C., Marsh T., Dhillon V., Knigge C., 2006, MNRAS, 365, 287: Detection of a period decrease in NN Ser with ULTRACAM: evidence for strong magnetic braking or an unseen companion

Dhillon V. et al., 2005, MNRAS, 363, 609: High-speed, multicolour optical photometry of the anomalous X-ray pulsar 4U 0142+61 with ULTRACAM

Feline W., Dhillon V., Marsh T., Watson C., Littlefair S., 2005, MNRAS, 364, 1158: ULTRACAM photometry of the eclipsing cataclysmic variables GY Cnc, IR Com and HT Cas

## 12. List of targets proposed in this programme

| Run | Target/Field | $\alpha$(J2000) | $\delta$(J2000) | ToT | Mag. | Diam. | Additional info | Reference star |
|---|---|---|---|---|---|---|---|---|
| A | Vela pulsar | 08 35 20.7 | −45 10 35 | 32 | V=23.6 | | Including overheads | |

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.

The data we require can only be obtained with ULTRASPEC and therefore are not in the archive as there has not yet been a science run with the camera.

13. Scheduling requirements

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

| Run | from | to | reason |
|---|---|---|---|
| A | 5-jan-07 | 15-feb-07 | Approximately, as we are committed to ULTRACAM runs on the WHT in late Autumn 2007 and early Spring 2008 and therefore need to avoid these dates. Note that any successful ULTRASPEC proposals will need to be scheduled together. |

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 improved 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$0.5mm from the mounting flange of the ESO cryostat in which it is installed. Furthermore, the CCD must be flat to approximately 100$\mu$m 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.