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–8**

Spectral eclipse mapping of accretion discs in Cataclysmic Variables

2. Abstract

Accretion discs are found in a wide range of astrophysical objects including young stellar objects, close binaries, and active galactic nuclei. Because they are difficult to spatially resolve, our understanding of accretion-disc structure and the process of accretion is still poor. We propose to use high-time resolution spectroscopy with ULTRASPEC on the 3.6-m to carry out spectral-eclipse mapping of the accretion discs in a range of Cataclysmic Variables (CVs). This study will allow not only the intensity distribution across the accretion disc to be ascertained, but also provide a unique way to determine the velocity field within the discs. These observations will determine whether or not spiral shocks and/or the impact of the accretion stream can cause deviations from Keplerian motion.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	Special3.6	2n	feb	g	$\leq 1.2''$	THN	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:

We propose to use an L3CCD called ULTRASPEC, which was commissioned in December on EFOSC. L3CCD's employ avalanche multiplication gain to eliminate readout noise and are thus good for high-speed, readout-limited spectroscopy. See Section 15 for further details.

6. Principal Investigator: C. Watson (University of Sheffield, UK, c.watson@sheffield.ac.uk)

CoI(s): S. Littlefair (University of Sheffield, UK), V. Dhillon (University of Sheffield, UK), T. Marsh (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: Accretion discs are found in a wide range of astrophysical objects, from young stellar objects and close binaries, to active galactic nuclei containing super-massive black-holes. Despite their importance and a long history of theoretical modelling of accretion discs, our understanding of the accretion process and the structure of accretion discs is still poor. This is largely due to the observational difficulties involved in spatially resolving accretion discs.

One of the best places to study accretion discs are Cataclysmic Variables (CVs), which typically consist of a late-type main-sequence star which fills its Roche-lobe and feeds material via an accretion stream into an accretion disc surrounding a white dwarf primary star. With several hundred systems known, CVs form the foundation of our understanding of accretion since their discs are bright over a wide range of energies, and their geometries are reasonably well-known. While CVs are too small and too far away to resolve directly, a number of methods exist which can resolve their accretion discs indirectly. One method is to use the information contained in the eclipse light-curves of high-inclination systems to reconstruct the spatial intensity distribution across the surface of the accretion disc (Horne 1985). Another method is that of Doppler tomography (Marsh & Horne 1988), which uses a time-series of spectra to map the line-emissivity of the disc in velocity space. This latter method provides no spatial information about where in the disc the line-emission arises. Thus, whilst both techniques have been immensely successful in providing information about the structure of accretion discs, neither technique provides information on the velocity field within the disc.

In order to interpret data on accretion discs, it is largely assumed that the velocity field is Keplerian. In the case of Active Galactic Nuclei (AGN), which are believed to host a super-massive black-hole surrounded by a parsec sized accretion disc, the disc can be used to determine a dynamical mass for the black-hole. The best example is NGC 4258, in which Miyoshi et al. (1995) associated masers with a thin disc in Keplerian motion around the central massive black-hole. In the case of CVs and X-ray binaries, Keplerian motion is often assumed in order to relate features in Doppler maps to spatial locations in the accretion disc and, in addition, such disc lines are also used to determine the compact object masses in these binaries.

It is not clear, however, that the velocity field of accretion discs is actually Keplerian. The formation of spiral shocks in the accretion discs of outbursting CVs (Steeghs, Harlaftis & Horne 1997), for example, may cause deviations from Keplerian motion. Furthermore, the region where the accretion stream (which is on a ballistic trajectory) impacts the disc may also cause a mixing of velocities. Magnetic-rotational stresses within the disc due to, e.g., Balbus-Hawley instabilities (which may provide the long-sought after viscosity source within accretion discs – Balbus & Hawley 1991; Hawley & Balbus 1991) could also provide another way of altering a disc's velocity-field. Indeed, in a study of the cataclysmic variable IP Peg, Ishioka et al. (2004) concluded that the behaviour of the disc was more complex than simple Keplerian motion. Furthermore, Greenhill et al. (1996) has also discovered sub-Keplerian motion of masers in NGC 1068. Should the velocity-fields of accretion discs not follow a Keplerian law, this would have an impact on our understanding of the location of line formation within discs, accretion disc structure and cause systematic errors in the determination of compact objects masses derived from observations of discs.

B) Immediate Objective: We shall use a technique called *spectral-eclipse mapping* to reconstruct the intensity distribution and velocity-field of the accretion discs in a selection of CVs. Spectral-eclipse mapping is a straight-forward extension of the original eclipse mapping technique of Horne (1985), except it relies (as the name suggests) on high-time resolution spectra taken through the eclipse of the accretion disc and white dwarf. The technique was first applied by Rutten et al. (1993, 1994) to the cataclysmic variable UX UMa, though only the integrated flux in the lines was used and the velocity information was ignored.

Recently, Ishioka et al. (2004) obtained 8-m Subaru spectra of the cataclysmic variable IP Peg during eclipse. From this they were able to model the line profile variations, and investigated in some detail both the line-emissivity distribution and velocity profile of the disc (see Fig. 1). While their simple model captures much of the phenomenology of the data, it still shows significant discrepancies which is thought to be due to non-Keplerian velocities within the disc. Unfortunately, the time-resolution obtained – and hence the spatial resolution they achieved on the disc – was low. This was for two reasons. First, despite the brightness of IP Peg (V $\sim$ 12 during outburst), 30-second exposures were still required on an 8-m telescope. Second, the CCD readout speed was 50-seconds, resulting in just one spectrum every $\sim$80-seconds. This restricted the spatial resolution of their data, and ideally one would want to sample faster in order to resolve smaller features.

We propose to use ULTRASPEC on the 3.6-m telescope at La Silla for our spectral-eclipse mapping study. This uses EFOSC and low-light-level (L3) CCDs to provide ultrafast spectroscopy with minimal dead-time (milli-seconds) and virtually no readout noise, and overcomes the weaknesses of conventional CCD detectors which prohibits high-speed spectroscopy of faint objects. This will allow us not only to determine the intensity distribution across the disc, but will provide a unique and unparalleled investigation of the velocity-field within the accretion discs of CVs.

In another application (PI:Marsh) we aim to examine white dwarfs using low resolution spectra obtained in the blue, with two targets (Z Cha and OY Car) in common. For the disc study proposed here, we require high resolution spectra covering Hα obtained in the red, and thus the data from the two proposals are incompatible.

8. Description of the proposed programme (continued)

C) Telescope Justification: High time-resolution spectroscopy is essential to the success of this project. In order to do this, high read-out speeds are required. In addition, since we wish to keep exposure times low, our spectra will be read-noise dominated. ULTRASPEC's L3CCDs solve both these problems, having both negligible readout-time and readout-noise. This instrument is only available on the 3.6-m La Silla telescope.
The new VPH#4 grism with a wavelength coverage of 6282 − 6773Å at a resolution of 2.9Å will allow us to observe the Hα and He I 6678Å emission lines in a number of eclipsing CVs at a better velocity resolution ($\sim$130 km^{-1}) than that obtained by Ishioka et al. (2004) in their study of IP Peg.
All of our eclipsing targets have magnitudes that range from V = 10–17, depending upon the state of the system. Typical magnitudes of the targets during outburst are V = 10–13. In the majority of the systems the accretion disc dominates the total light of the binary system. Using 40-second exposures (in grey-time, 1$''$ slit, 1$''$ seeing, and an airmass of 1.3), we estimate that we will obtain a signal-to-noise of approximately 16 per pixel for a 15th magnitude CV. Given that we are heavily oversampling in the spectral direction, this will give us a signal-to-noise of 40 per resolution element – which is adequate for our purposes. An exposure time of 40-seconds (we shall run faster in the case of the system being brighter than V=15) essentially means that our spatial resolution will be more than twice as good as what Ishioka et al. (2004) were capable of with their 80-second cycle time. We should also note that with the same setup, but not using the L3 CCDs of Ultraspec, we would only obtain a signal-to-noise of $\sim$7 per pixel, and read-out time would considerably degrade our spatial resolution. Furthermore, the increase in signal-to-noise as a result of using L3CCD's on the 3.6-m is the equivalent of using a conventional CCD on a 6-m class telescope. For fainter targets which also, typically, have shorter eclipse durations, we shall cover more than one eclipse in order to boost our signal-to-noise further and ensure that we have the same quality of data for the short duration eclipses as we shall obtain for the longer duration eclipses.
A sufficient number of our targets are visible after the 1st December such that we can easily observe several eclipses on any night between 1st December and the end of March. We have plotted the times of eclipse of our targets for a random date (in this case for observations starting on the 15th February 2008). This shows there are ample eclipses visible spaced throughout the night.

D) Observing Mode Justification (visitor or service): ULTRASPEC is offered on a shared-risk, collaborative basis with Vik Dhillon (University of Sheffield) and Tom Marsh (University of Warwick). The observations will be carried out by the ULTRASPEC team in visitor mode.

E) Strategy for Data Reduction and Analysis: The investigators on this proposal have a wealth of experience of indirect imaging techniques. Tom Marsh (University of Warwick) was one of the pioneers of the Doppler tomography technique (see Marsh & Horne 1988). Vik Dhillon (University of Sheffield) was one of the co-investigators for the original spectral-eclipse mapping technique (see Rutten et al. 1993, 1994). Chris Watson is also experienced with the technique of Roche tomography, an indirect imaging technique that uses time-series echelle spectra to reconstruct the line-intensity distribution on Roche-lobe filling donor stars in CVs and close binaries. This technique was used to spatially resolve starspots on the donor stars in CVs for the first time (see Watson et al. 2006, and references therein). Finally, Stuart Littlefair is experienced with parameterised accretion disc models, and recently used such models to measure the mass of the donor star in the eclipsing system SDSS 1035 and hence identify the first brown dwarf donor star in an accreting binary (Littlefair et al. 2006). All the investigators have a sound track record in indirect-imaging of accretion discs and CVs, and the relevant software is readily available. Tom Marsh and Vik Dhillon are both responsible for the operation of ULTRASPEC, and data acquisition and reduction is not an issue.

REFERENCES

Balbus S., Hawley J., 1991, AJ, 376, 214
Greenhill L., Gwinn C., Antonucci R., Barvainis R., 1996, ApJL, 472, L21
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Littlefair S. et al., 2006, Science, 314, 1578L
Marsh T., Horne K., 1988, MNRAS, 235, 269
Miyoshi M. et al., 1995, Nature, 373, 127
Rutten R. et al., 1993, Nature, 362, 518
Rutten R., Dhillon V., Horne K., Kuulkers E., 1994, A&A, 283, 441
Steeghs D., Harlaftis E., Horne K., 1997, MNRAS, 290, 28
Watson C., Dhillon V., Shahbaz T., 2006, MNRAS, 368, 637

8. Attachments (Figures)

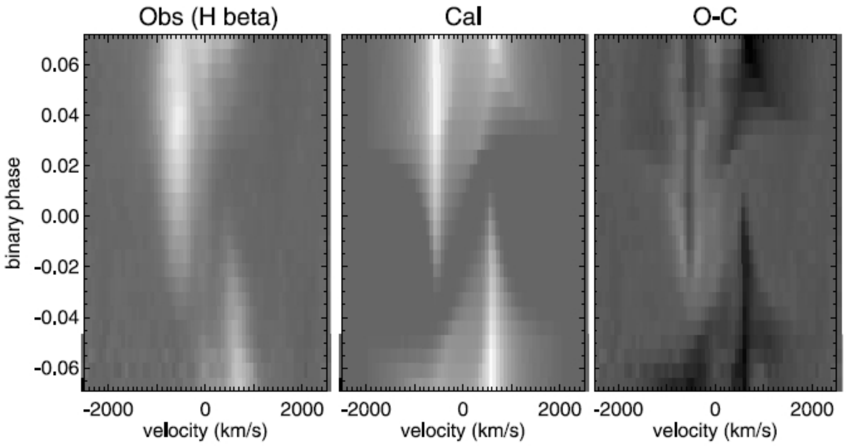

Fig. 1: The left panel shows the Hβ profiles from IP Peg's accretion disc observed by Ishioka et al. (2004) as a function of time. Time increases from bottom to top, with mid-eclipse at binary phase = 0.0. Bright greyscales indicate enhanced line emission. Outside eclipse the emission lines have the well-known double-peaked profiles that come from Doppler shifting in accretion discs. In this close up of the eclipse of the disc, first we can see the approaching side of the disc obscured by the donor star, affecting the blue-shifted parts of the line, followed soon after by the red-shifted counterpart. The middle panel shows a model fit to the emissivity and velocities within the disc. While this captures the general morphology of the data quite well, there are still significant discontinuities (right-hand panel) that are thought to be due to a non-Keplerian velocity-field. Using ULTRASPEC we shall obtain higher time- and velocity-resolution data on $\sim$7 eclipsing CVs.

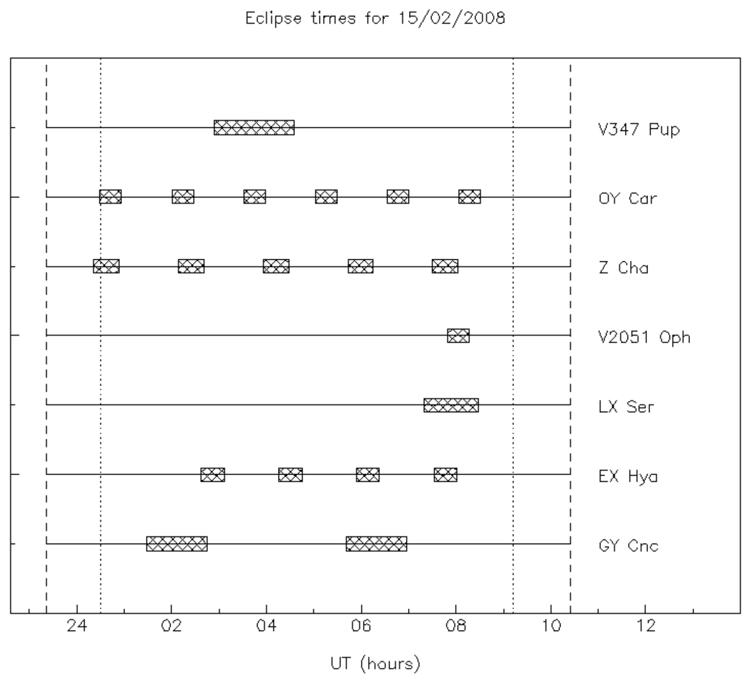

Fig. 2: Eclipse times of the target CVs calculated for a random date. The vertical dashed line indicates sunrise/sunset, and the dotted line indicates astronomical twilight. The hashed boxes indicate times of accretion disc eclipses (target names are shown on the right). These include overheads to ensure that data is taken before and after eclipse so that we can calibrate the spectra out-of-eclipse, and also allow for errors in the ephemeris so that we avoid obtaining a partial eclipse. It should be noted that some systems have substantially shorter eclipse durations, and for this reason we shall observe more than one eclipse for these systems.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: Given the intermediate resolution of the spectra, no advantage is gained by carrying out these observations in dark time. The sky background during bright time, however, does reduce our signal-to-noise and, since relatively high signal-to-noise is required, we request that these observations are carried out in grey time such that we fully maximise the unique capabilities of ULTRASPEC.

Time Justification: (including seeing overhead) Each eclipse typically lasts a fraction of 0.1–0.2 of the orbital period of the CV. We also require to observe the system just before and after eclipse in order to calibrate the out-of-eclipse spectrum. In order to do this, while simultaneously guarding against erroneous eclipse timings or accidentally missing portions of eclipses, we require to spend a fraction of $\sim$0.3 of the binary period on each system. This alone would take approximately 1 night to cover one eclipse of each system. In order to increase our signal-to-noise on the fainter CVs (which typically also have shorter eclipse durations) so that they match the quality of data we shall obtain on the brighter, longer-period CVs, we typically would like to spend 2–3 hours on each system. This will take 2 nights for our 7 candidates.

Calibration Request: Standard Calibration

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

077.D-0579; VLT+UVES, "*Does the eclipsing Halo X-ray binary 2S,0921–630 contain a massive neutron star or a low-mass black hole?* Data being analysed.

079.D-0431; VLT+UVES, *Mapping stellar activity in interacting binary stars: Testing stellar dynamo theories.* To be observed August 2007

079.D-0440; NTT+EMMI, "*Testing the Thermal Relaxation Oscillation Theory of contact binary star evolution: Indirect imaging of W Crv.* To be observed April 2007.

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

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

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

Watson C., Dhillon V., Shahbaz T., 2006, MNRAS, 368, 637: *Roche tomography of cataclysmic variables - III. Star-spots on AE Aqr*

Feline W. et al., 2005, MNRAS, 364, 1158: *ULTRACAM photometry of the eclipsing cataclysmic variables GY Cnc, IR Com and HT Cas*

Thoroughgood T. et al., 2005, MNRAS, 357, 881: *The component masses of the cataclysmic variable V347 Puppis*

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	V347 Pup	06 10 33.5	-48 44 25.9	3.0	13–16		P = 334 mins	
A	OY Car	10 06 22.4	-70 14 04.9	3.0	12–17		P = 91 mins	
A	Z Cha	08 07 28.2	-76 32 01.2	3.0	12–15		P = 107 mins	
A	V2051 Oph	17 08 19.1	-25 48 30.8	3.0	13–17		P = 90 mins	
A	LX Ser	15 38 00.1	+18 52 03.2	3.0	13–17		P = 228 mins	
A	EX Hya	12 52 24.4	-29 14 56.7	3.0	10–14		P = 98 mins	
A	GY Cnc	09 09 50.00	+18 49 47.0	3.0	12–18		P = 253 mins	

Target Notes: Magnitudes given are the range observed for the system. The orbital period, P, in minutes is given in the Additional info column.

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.

These observations are unique, and can only successfully be carried out using ULTRASPEC.

13. Scheduling requirements

3. Unsuitable period(s) of time

Run	from	to	reason
A	01-oct-07	30-nov-07	Poor target visibility

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 ~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±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.