

## Mid-Infrared Ground-Based Astronomy

Patrick Roche  
Oxford University



## Topics

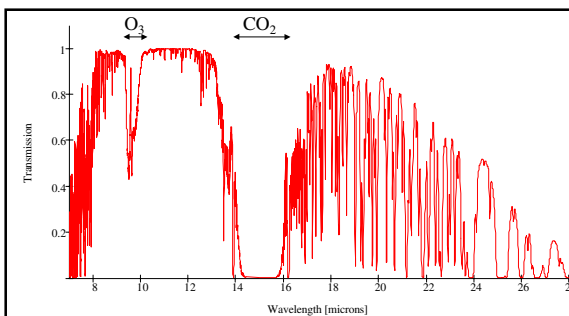
- The sky and telescopes
- The instruments
- Observing techniques
- Sensitivity
- Niches

## Ground-based Mid-IR Astronomy

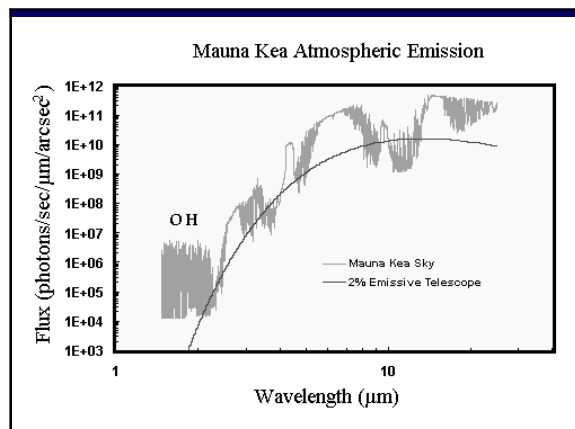
- Observations of cool objects - dust, gas, molecules
- Large telescope apertures give high resolution  
 $\lambda/D = 0.3$  arcsec at  $12\mu\text{m}$ , but need good conditions and guiding to realise this
- Windows of good/fair transmission between 8-13 and 16-25  $\mu\text{m}$
- Benefit from cold high dry sites (Mauna Kea/Chile) and low emissivity, high cleanliness
- Suffers huge thermal background which compromises sensitivity compared to space missions, but high resolution of compact objects to complement Spitzer.
- Greatest relative gains at high spatial and spectral resolution

## Background Signals

- Atmospheric transmission depends primarily on water vapour column above site
- Mauna Kea good conditions  $\sim 1\text{mm}$  PWV (CSO  $\tau \sim 0.05$ ), but can be much higher, and generally higher at other sites.
- Sky Noise - unstable weather, thin cirrus and other structured cloud, wind-borne dust, bugs, birds....
- Need a stable telescope, uniform clean mirrors,
- Major sources of background : Sky, Telescope Mirrors + support structures, Instrument window
- Background cancellation via chopping secondary, want small stable residual offset signals



- Telescope emission peaks at  $\sim 15\mu\text{m}$ , corresponding to temperatures of  $\sim 270 - 290$  K
- Sky temperature similar at most wavelengths, but  $\text{O}_3$  emission arises from higher and colder layers





## VLT and Gemini

### VLT

- 30 arcsec chop throw (20" if guiding on both beams) at ~5Hz
- Beryllium secondary : Al coating, retractable baffle
- altitude 2635m

### Gemini

- 15 arcsec chop throw, currently can only guide on 1 beam.
- Glass secondary with Ag coating, central hole, retractable baffle
- Altitude 2715, 4214m

## Chopping Limits

- Compact objects: chop on-chip, maximise detected source signal.
  - Standard beamswitching
  - 4-point chop - nod
- Typically integrate for ~30 sec, chopping at ~3Hz then nod telescope.

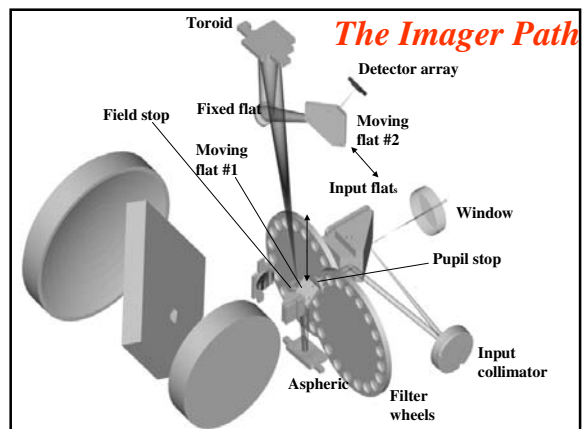
## Thermal Region Camera and Spectrometer (T-ReCS) for Gemini-S



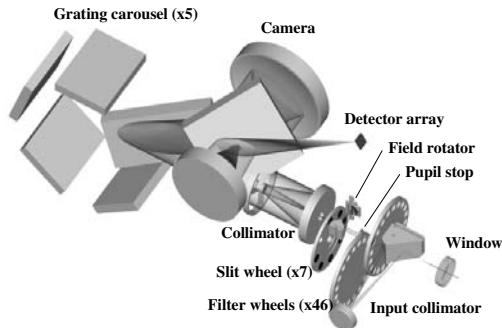
- Built by the University of Florida
- Single plate scale mid-IR imager
  - Plate Scale: 0.09 arcsec/pixel
- Pupil and window imaging modes
- Low/moderate (R~1000) spectroscopy in 10 & 20  $\mu$ m bands
- Detector: 240x320 pixel Raytheon Si:AS IBC
- Wavelength Range: ~5 to 25  $\mu$ m
- Cooled by a 2-stage cooler
- Cryostat window selection/protection
- Operating on Gemini-S

## Michelle : Mid-Infrared echelle spectrometer and imager for Gemini-N

- Built by the UKATC, Edinburgh
- Transferred from UKIRT to Gemini-N on long-term loan from April 2004
- 5-25 $\mu$ m imager/spectrometer with low, moderate and high spectral resolution modes (200 < R < 20000) selectable from 5 cold gratings
- 0.10 arcsec/pixel for imaging
- 0.2 arcsec/pixel spectroscopy
- Cooled by 2-stage cooler + J-T system for the detector



## The Spectrometer - Cold Optics



## VISIR on the VLT

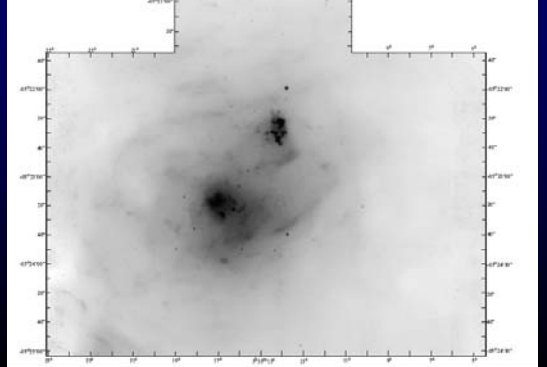


- Pixel scales 0.08, 0.13"/pix
- Twin Boeing 256 x 256 arrays
- R~350, 3000, 25000 with slits of 0.4, 0.7 arcsec
- Long slit and cross-dispersed modes available with the echelle
- Boeing detector currently suffers from excess noise (probably from thermal instability in cryosystems)

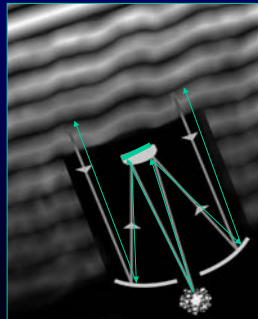
## Chopping

- The telescope secondary mirror rocks in a quasi-square wave pattern at a few Hz, displacing the image of the object by ~20 arcsec on the detector. This allows the weak emission from the astronomical object to be detected differentially on top of the large thermal background
- The mirror position is stabilised with fast guiding at one or both chop positions, ideally chop in azimuth, but reduction then tricky
- Chop throw should be symmetric about the optical axis, and angles should be small so that image quality is maintained.
- BUT small throws mean that for extended objects, there may be residual flux in the reference position. For extended regions, reconstruction of chopped signals will be needed with consequent increases in observing time and complexity of data reduction and deterioration of S/N. Not much experience here, but.....

Max/UKIRT mosaic reconstruction of central 5' of Orion  
Robberto et al 2005  
ApJ 129, 1534

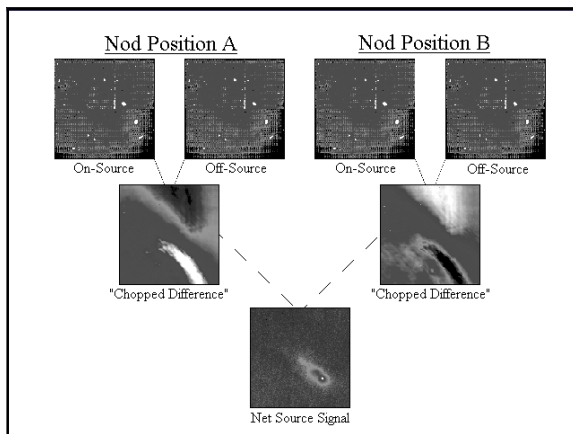
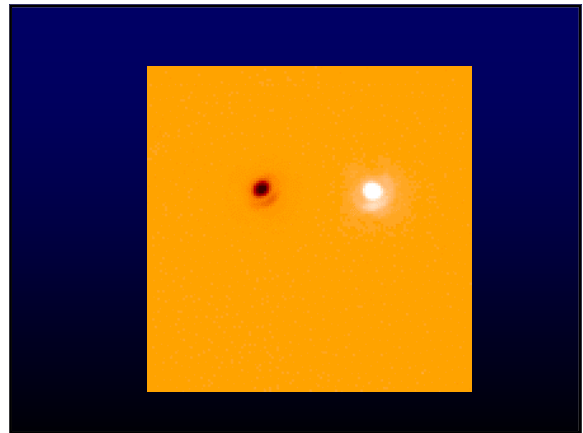
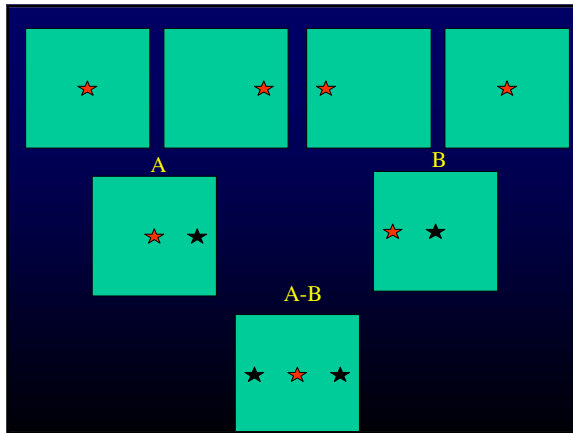


- Big telescopes are better for chopping
- Beams separate higher in the atmosphere, and have more overlap on primary mirror
- Chop throw of 20 arcsec corresponds to ~14mm in telescope focal plane
- and a motion of ~11mm on the Primary c.f. diameter of 7.9m



## Chopping and Nodding

- Motion of secondary mirror, means that the detector beam falls on slightly different parts of the primary mirror, which have different defects, dust etc, leading to a radiative offset between the two chop positions.
- This is compensated by Nodding the telescope so that the object and reference positions are switched.
- Beamswitching :
  - Nod the telescope by a distance equal to the chop throw along the chop axis
- 4-point nod
  - Nod the telescope orthogonal to the chop axis and by an amount equal to the chop throw along the axis



### Signal and Noise

- A-B gives net signal corrected for radiative offset
- BUT flexure and temperature changes mean that offset changes with time, so take data in sequence A,B,B,A to remove linear gradient in offset.
- With beamswitching on-chip, final stacked frame has
  - one image with 2 x signal + 2 x sky background
  - two images with 1 x signal + 2 x sky background
  - Coadding all images gives an increase in S/N of  $2/\sqrt{3}$  (30% in time)
- 4-point nod has 4 images with 1 x signal and 2 x background
  - Coadding all images has same S/N as central beamswitched image.

### Sensitivity

- BLIP - Background Limited Performance
  - With backgrounds  $>10^{10}$  photons/sec/  $\mu\text{m}^2$ , should get close to BLIP in all observing modes
  - Requires detector stability and performance, adequate filling of wells, efficient detector read schemes, low electrical noise
  - Theoretical Sensitivity depends on
    - Throughput of atmosphere, telescope & instrument
    - Detector QE (and noise sources - dark and read), read efficiency
    - Emission from sky, telescope and instrument window
    - Telescope efficiency, chop duty cycle, nod settle times, clocking efficiency

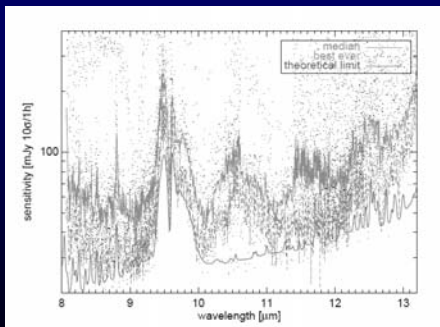
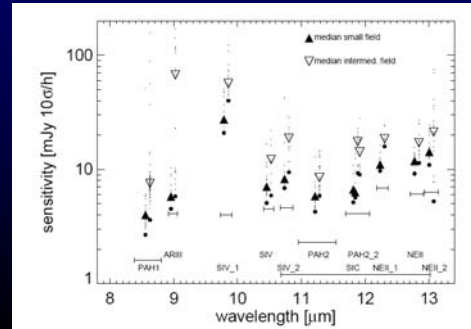
### Sensitivity

- In the background limit, the sensitivity is given by the square root of the number of photons detected, which at 10  $\mu\text{m}$  will be:
 
$$\text{NEFD} = 2.57 \times 10^{-4} \sqrt{[(B_{\nu,T}) \epsilon \Omega R] / (t Q A)} \text{ Jy}$$
- where  $B_{\nu,T}$  is the Planck function,  $\epsilon$  the system emissivity,  $\Omega$  the solid angle seen by the detector, R the spectral resolving power, t the instrument throughput, Q the detector quantum efficiency, and A the telescope area.
- For Gemini with a collecting area of 49  $\text{m}^2$  at an effective temperature of 275K at 10  $\mu\text{m}$ , this becomes:
 
$$\text{NEFD} = 2.6 \theta \sqrt{[(\epsilon R) / (t Q)]} \text{ mJy}$$
 where  $\theta$  is the pixel side in arcsec.
- An instrument with good detector efficiency (50% QE) and instrument throughput (50%) on Gemini with a system emissivity of 4% could reach the following sensitivity for observations through a 1  $\mu\text{m}$  bandwidth filter at 10  $\mu\text{m}$  and summed over a 1 arcsec<sup>2</sup> region.
 
$$10 \text{ sigma } 1 \text{ hr} = 0.6 \text{ mJy}$$

## Sensitivity

- In Practice, we have to consider the overheads of chopping and nodding:
  - Chop duty cycle is <80%
  - Detector read efficiency depends on read rate - worst for fastest read rates.
  - Detector stability is also affected by read rates - detector self-heating at high rates,  $1/f$  noise at low rates.
  - flux excluded from small apertures
  - Differential measurements from chop give  $\sqrt{2}$  increase in noise.
  - achieved sensitivities are close to BLIP under best observing conditions:
    - On Gemini Best Achieved Point-Source Sensitivity:  $10.8 \mu\text{m}$  (N Band),  $10\sigma$ , 1 hour = 1mJy of chopped integration
    - Best Achieved Angular Resolution:  $0.30''$  FWHM
    - $10.8 \mu\text{m}$  (N Band), approximately diffraction-limited
- The sensitivity at  $20 \mu\text{m}$  is lower as a result of the high sky emissivity (typically 40% or so) and the increased diffraction-limited image size which requires the use of larger apertures, although the higher detector quantum efficiency provides some compensation.
- Need good stable low water vapour conditions – true queue scheduling

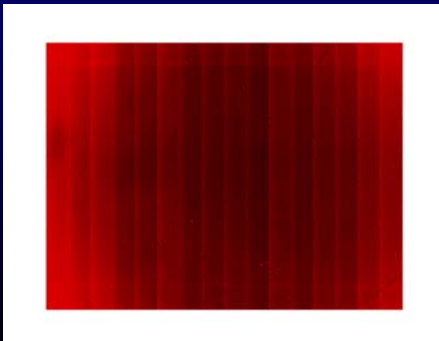
## VLT VISIR Commissioning results



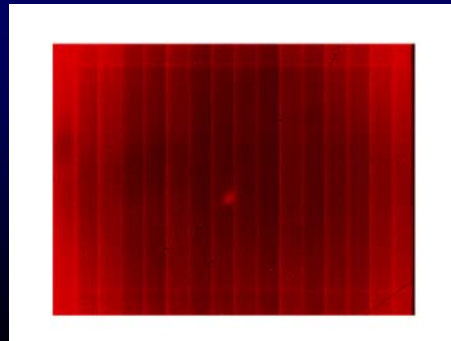
## Time Overheads

- Acquisition - similar to other instruments -
  - guide star acquisition with PWFS with Gemini
- Chopping - ~70% duty cycle, but also typically need to synchronise detector read cycle to chop sequence
- Nod slew time + settle time for guiding
- Currently on-source integration time is typically ~ 25% of the total elapsed time - this has to be added onto the time requested for Gemini imaging
- There is less experience with spectroscopy, but overheads are probably similar.
- Mid-IR observing on the ground is inherently inefficient, and needs good conditions for sensitive observations. Variations of factors 3 to 5 in sensitivity lead to a real premium on good conditions

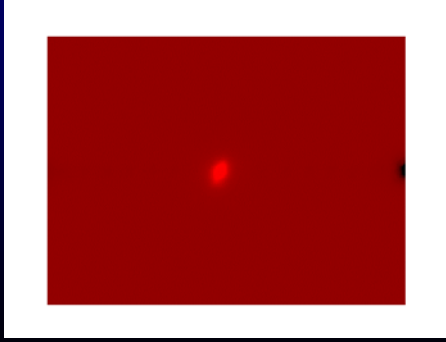
## TReCS Data - Sky



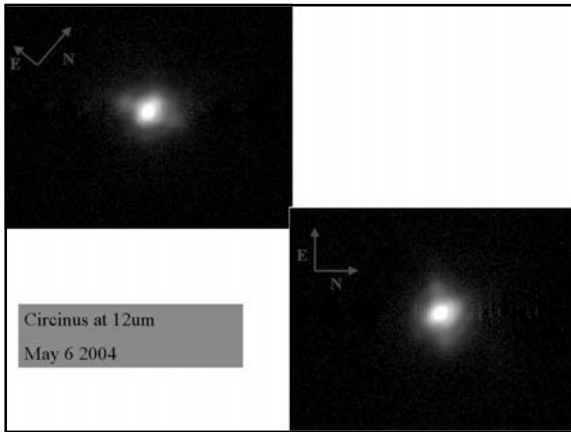
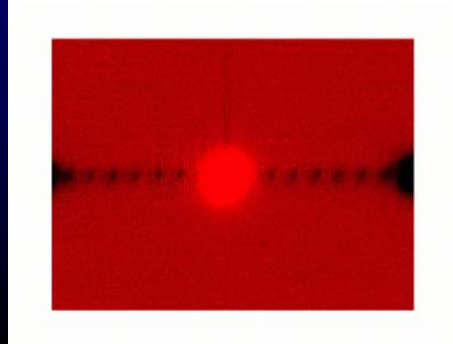
## TReCS Data – Bright Object



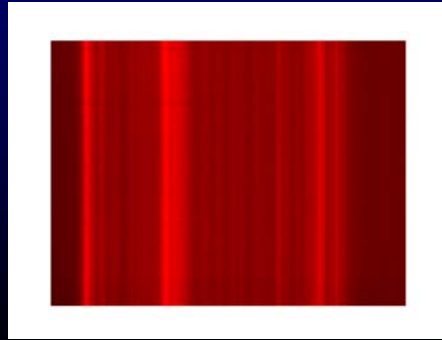
*TReCS Data – Chop (log plot)*



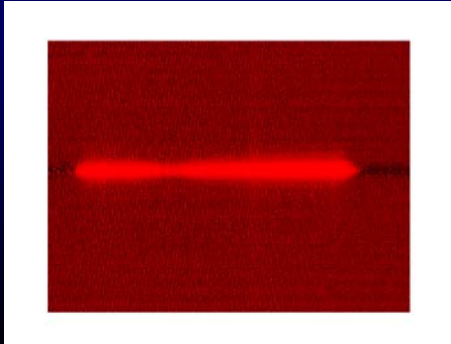
*TReCS Data – Chop (Linear plot)  
Showing Detector Cross Talk*



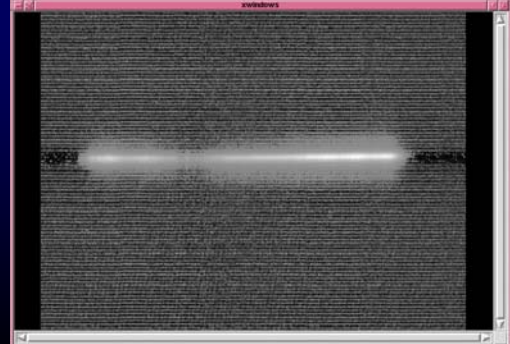
*TReCS Data – Spectroscopic sky*



*TReCS Spectroscopy- Object*

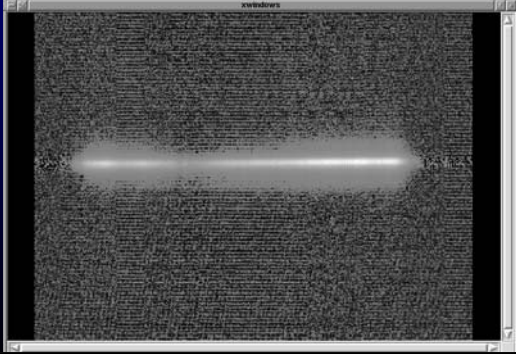


*TReCS Spectroscopy- Object*

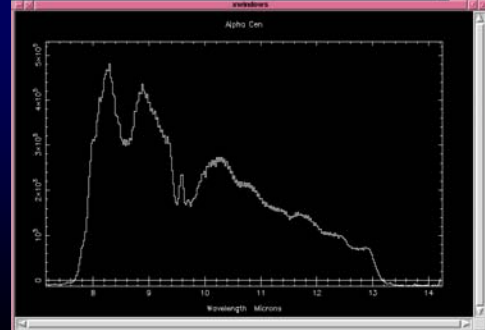




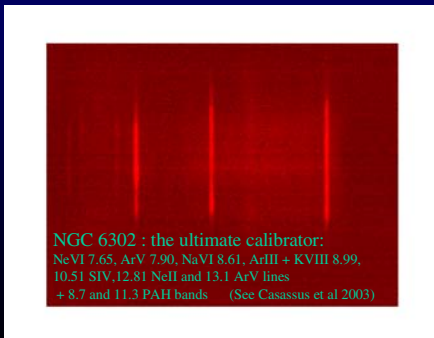
### TReCS Spectroscopy- patched



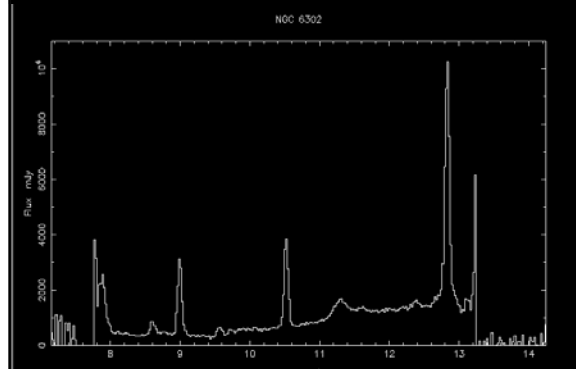
### TReCS Spectroscopy- Standard



### TReCS Spectroscopy- calibration NGC 6302

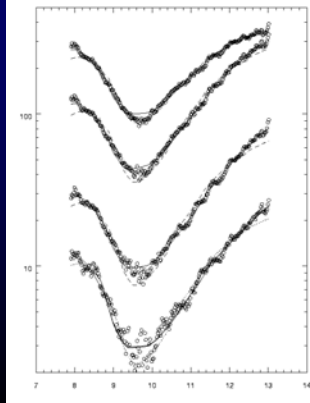


### TReCS Spectroscopy - NGC 6302



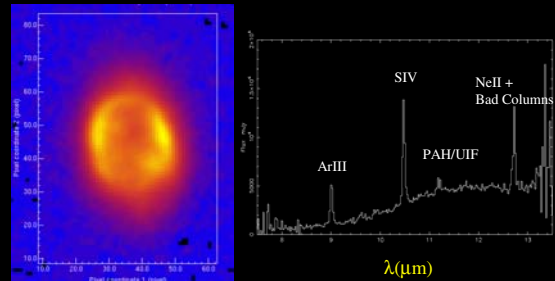
### TReCS Spectra Circinus

Spectra extracted on sub-arcsec scales  
 Silicate absorption increases to the East of the nucleus  
 [SIV] emission  
 PAH emission extends away from nucleus

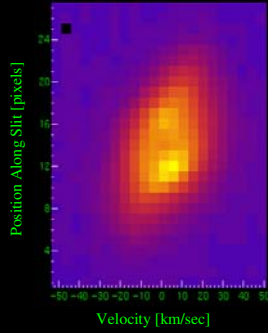


### Dissecting the planetary nebula NGC 6572 - Imaging and low-resolution spectroscopy

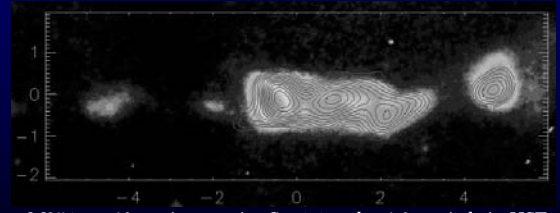
Michelle Commissioning UKIRT, 2001.



**Dissecting the planetary nebula NGC 6572**  
**- Velocity Resolved Spectroscopy of SIV line.**



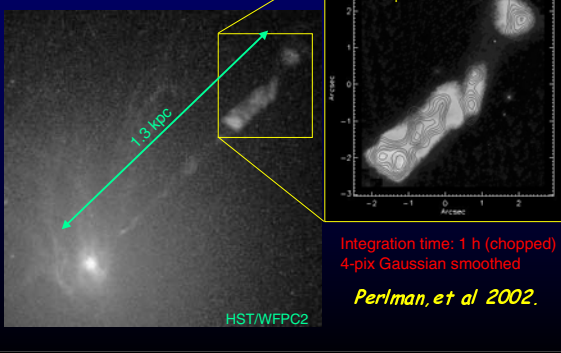
**The jet of M87 at 10 μm**  
**Eric Perlman et al. (UMBC)**



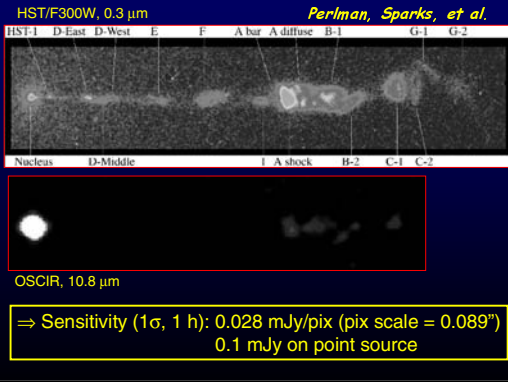
M87 jet at 10 μm (contours) – Gemini, and at 1.6 μm (color) –HST  
 Deepest ever taken in the mid IR.

Knots A, B, C (2 hours); FWHM = 0.5”  
 Nucleus (outside the field) is pointlike

**M87 JET**  
**Knot A/B Complex**



**M87 JET**



**TReCS images of SN1987A**

Bouchet et al (2004) ApJ 611, 394

Detection of the inner equatorial ring and the SN ejecta  
 Integrated flux ~ 10mJy, central peak ~0.3 mJy!

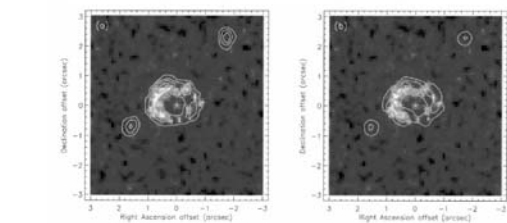
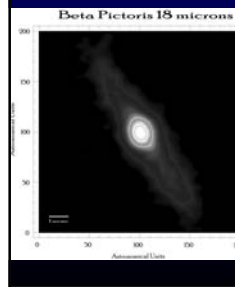


FIG. 2.—TReCS 10 μm images of SN 1987A, smoothed to 2 pixel (0.7”) resolution, overlaid with contours of the images obtained (a) in the H $\alpha$  line (1.083 μm) with OSIRIS at the CTIO Blanco telescope at day 5749 and (b) through the F658N filter (Ho and [N II] 6583) with HST at day 5555. The HST image is smoothed to 1.2 pixel (0.7”) resolution. The central source is not seen in any of the two overlays, whereas it is detected at 10 μm.

**The disk around Beta Pictoris**  
**Probing the inner disk**



ESO

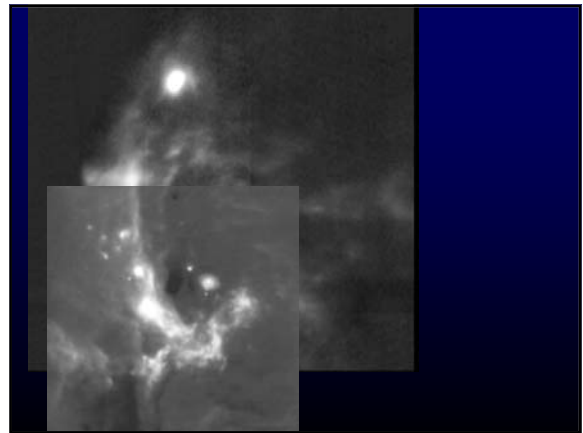
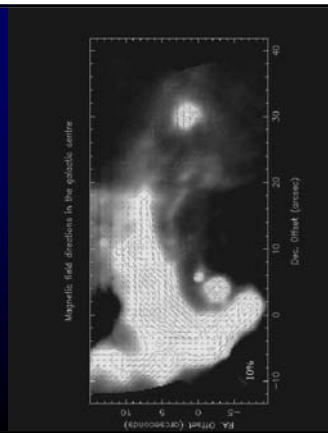


Potential for new modes.

Michelle has its own waveplate in the calibration unit for imaging and spectropolarimetry

Dust grain alignments, magnetic field directions at subarcsec resolutions.

Dust grain properties



## MIDI – High spatial resolution with the VLTI

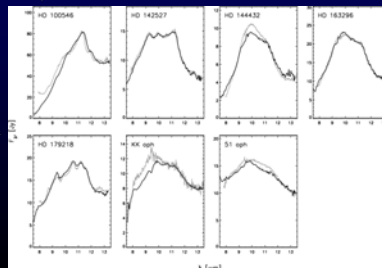
Interferometry on hundred metre baselines

Bright compact sources  $>1 \text{ Jy}$  @  $10\mu\text{m}$

Spectral size information at  $R \sim 30$

H AeBe Stars

Half-light radii 1-5 AU



## Conclusions:

- Michelle is about to undergo spectroscopic SV on Gemini-N while TReCS is available now on Gemini-S. VISIR is being made available on VLT.
- TReCS is best for high spatial resolution spectroscopy at low spectral resolution.
- Detailed investigation of compact mJy sources at high spatial resolution over small ( $<30$  arcsec) fields, with the potential for mosaicing over larger areas.
- Further sensitivity gains available through improved observing efficiency, but especially from true queue scheduling
- Highest sensitivity for compact objects
- Complementary to SPITZER, NGST