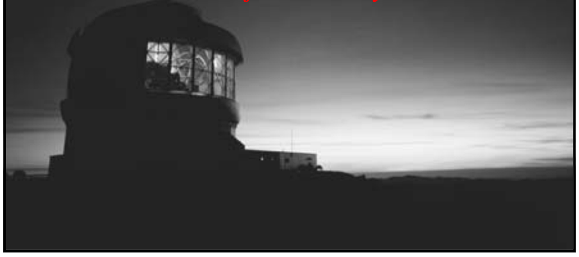
Mid-Infrared Ground-Based Astronomy

Patrick Roche
Oxford University



Topics

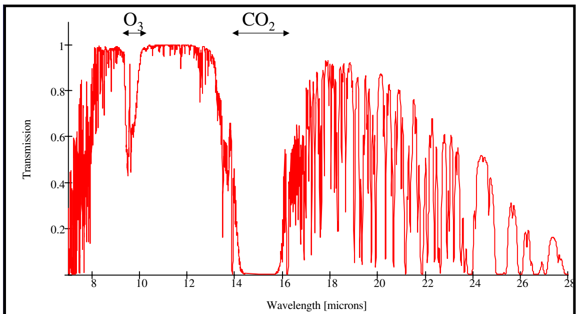
- The sky and telescopes
- The instruments
- Observing techniques
- Sensitivity
- Niches

Ground-based Mid-IR Astronomy

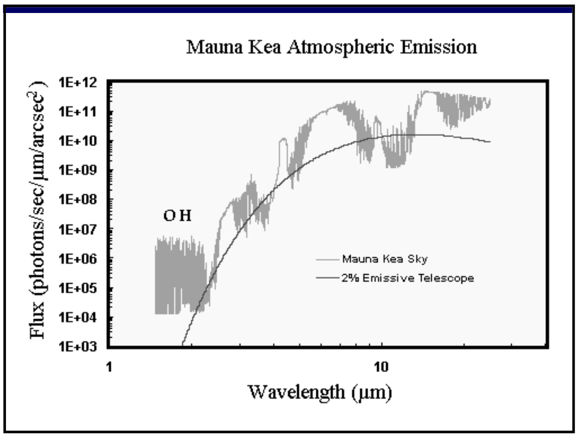
- Observations of cool objects - dust, gas, molecules
- Large telescope apertures give high resolution
  λ/D = 0.3 arcsec at 12μm, but need good conditions and guiding to realise this
- Windows of good/fair transmission between 8-13 and 16-25 μm
- Benefit from cold high dry sites (Mauna Kea/Chile) and 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

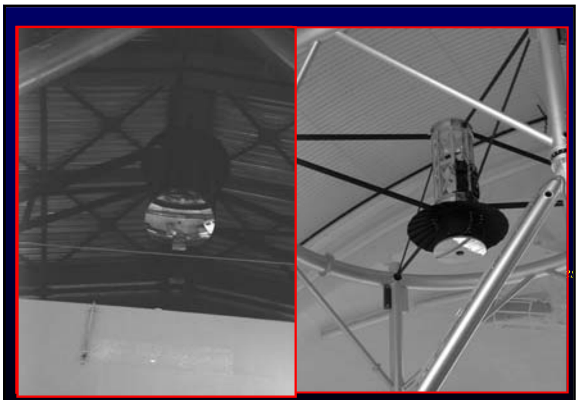
Background Signals

- Atmospheric transmission depends primarily on water vapour column above site
- Mauna Kea good conditions ~1mm PWV (CSO tau ~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 ~15μm, corresponding to temperatures of ~270 - 290 K
- Sky temperature similar at most wavelengths, but 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

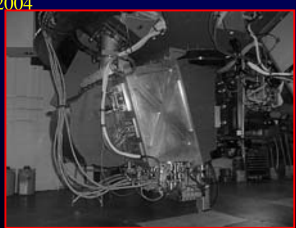
- Compact objects: chop on-chip, maximise detected source signal.
  - Standard beamswitching
  - 4-point chop - nod
- Typically integrate for ~30 sec, chopping at ~3Hz then nod telescope.

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

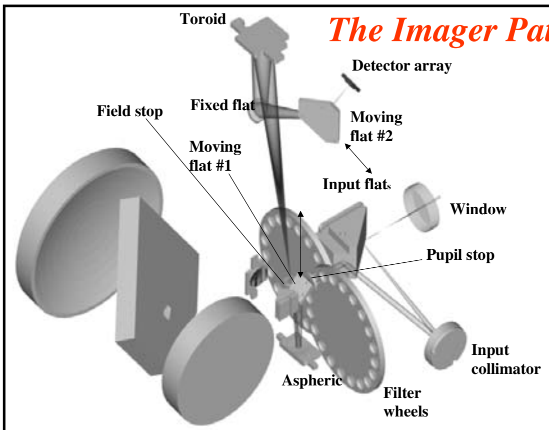
- Built by the University of Florida
- Single plate scale mid-IR imager
  - Plate Scale: 0.09 arcsec/pixel
- Pupil and window imaging modes
- Low/moderate (R~1000) spectroscopy in 10 & 20 μm bands
- Detector: 240x320 pixel Raytheon Si:AS IBC
- Wavelength Range: ~5 to 25 μm
- Cooled by a 2-stage cooler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

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

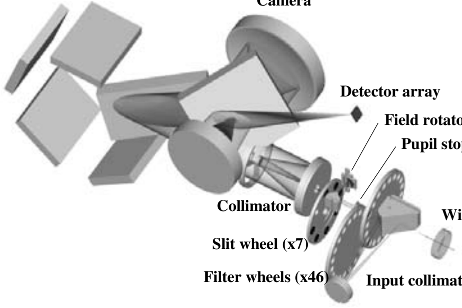
- Built by the UKATC, Edinburgh
- Transferred from UKIRT to Gemini-N on long-term loan from April 2004
- 5-25μm imager/spectrometer with low, moderate and high spectral resolution modes (200< R <20000) selectable from 5 cold gratings
- 0.10 arcsec/pixel for imaging 0.2 arcsec/pixel spectroscopy
- Cooled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



The Imager Path



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)

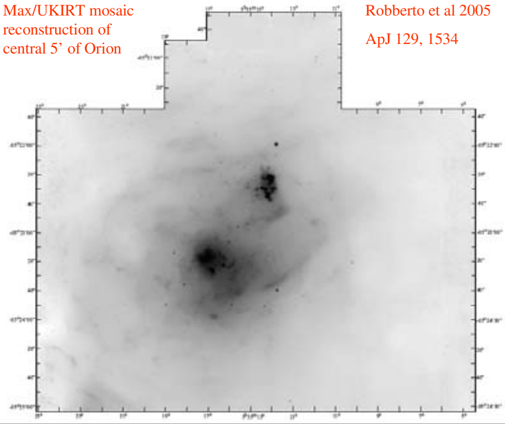
Chopping

- 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…..

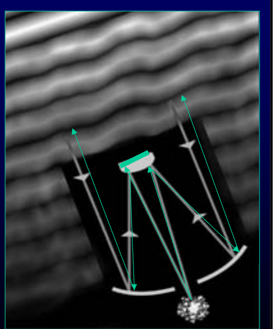
Max/UKIRT mosaic reconstruction of central 5' of Orion

Robberto et al 2005

ApJ 129, 1534

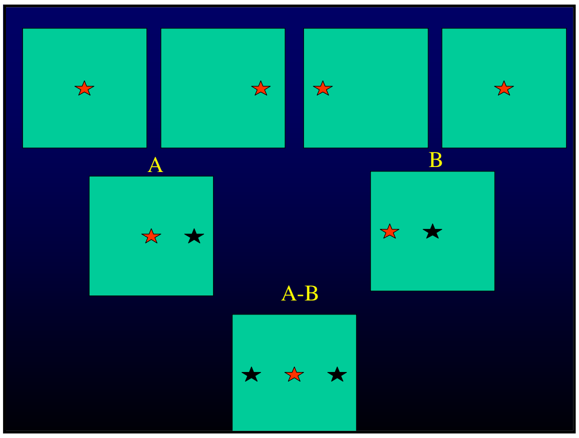


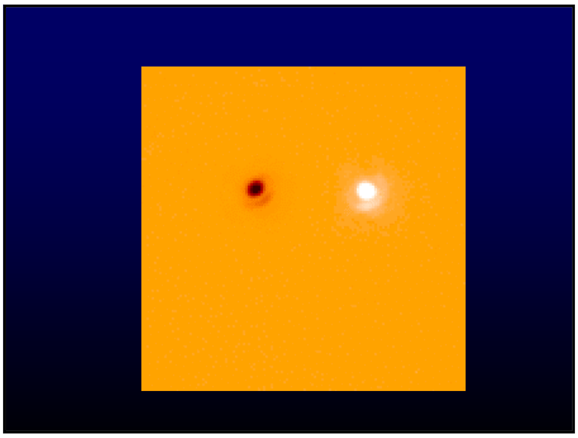
- Big telescopes are better for chopping
- Beams separate higher in the atmosphere, and have more overlap on primary mirror
- Chop throw of 20 arcsec corresponds to ~14mm in telescope focal plane
- and a motion of ~11mm on the Primary c.f. diameter of 7.9m

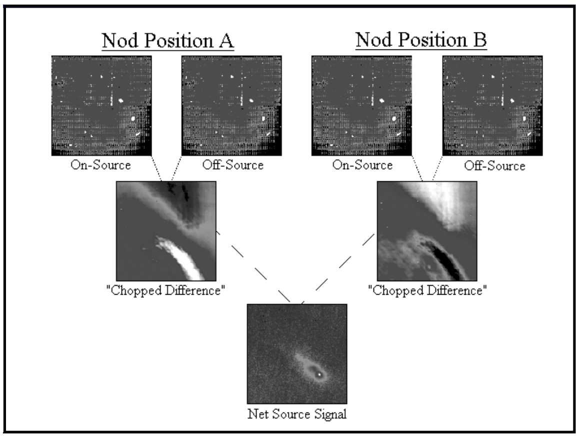


Chopping and Nodding

- 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/ $\mu m/m^2$, 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 effciency

Sensitivity

- In the background limit, the sensitivity is given by the square root of the number of photons detected, which at 10 µm will be:

  $$\mathrm{NEFD} = 2.57 \times 10^{-4} \sqrt{[(B_{(\nu,T)}\, \varepsilon\, \Omega\, R) / (t\, Q\, A)]}\ \mathrm{Jy}$$

- where $B_{(\nu,T)}$ is the Planck function, ε the system emissivity, Ω 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 m^2 at an effective temperature of 275K at 10 µm, this becomes:

  $$\mathrm{NEFD} = 2.6\, \theta \sqrt{[(\varepsilon\, R) / (t\, Q)]}\ \mathrm{mJy}$$ where θ 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 µm bandwidth filter at 10 µm and summed over a 1arcsec^2 region.

  10 sigma 1hr = 0.6 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:

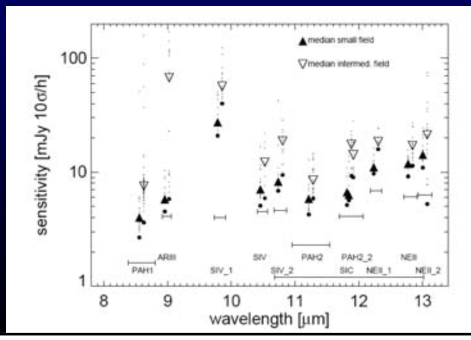
    On Gemini Best Achieved Point-Source Sensitivity:

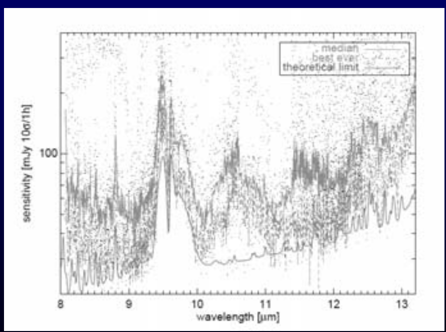
    10.8 µm (N Band), 10σ, 1 hour = 1mJy of chopped integration

    Best Achieved Angular Resolution: 0.30" FWHM

    10.8 µm (N Band), approximately diffraction-limited
- The sensitivity at 20 um 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





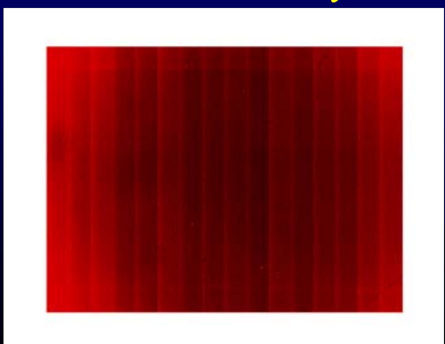
Time Overheads

- Acqusition - 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

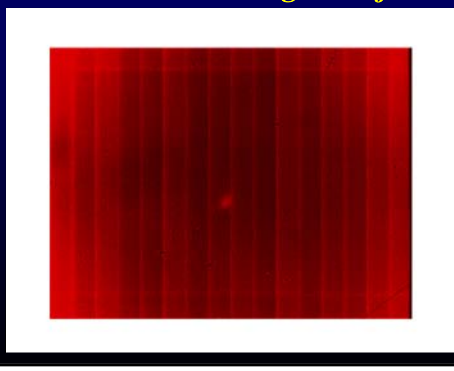
- There is less experience with spectroscopy, but overheads are probably similar.

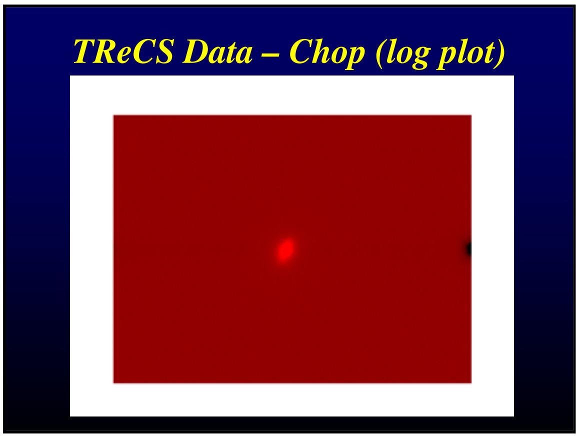
- Mid-IR observing on the ground is inherently inefficient, and needs good conditions for sensitive observations. Variations of factors 3 to 5 in sensitivity lead to a real premium on good conditions

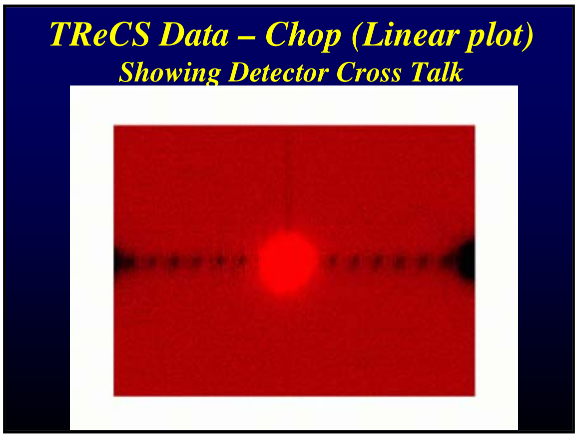
TReCS Data - Sky

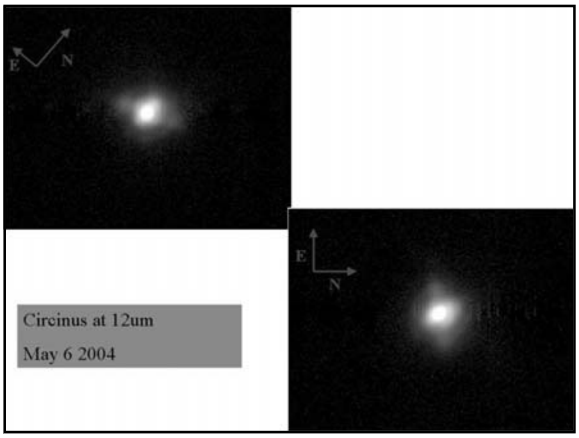


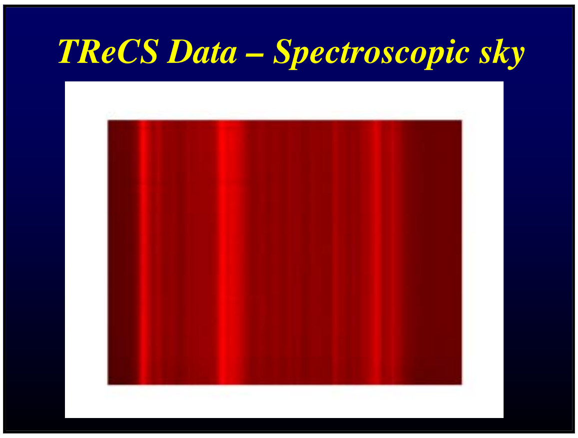
TReCS Data – Bright Object

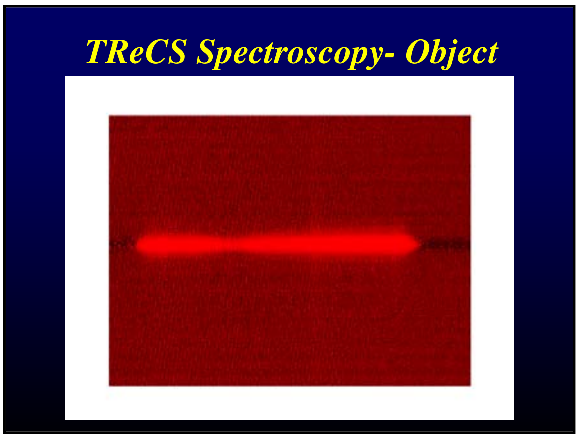


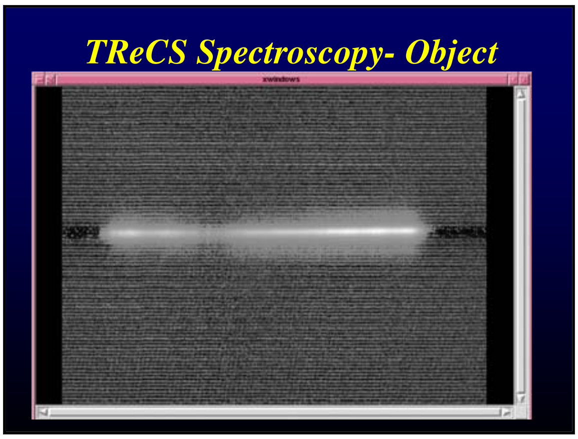

TReCS Data – Chop (log plot)

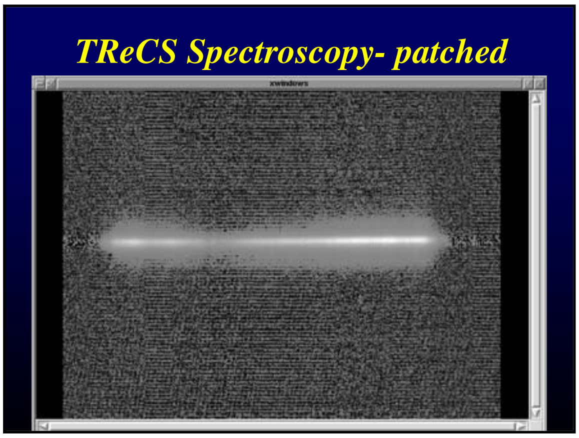

TReCS Data – Chop (Linear plot)
Showing Detector Cross Talk

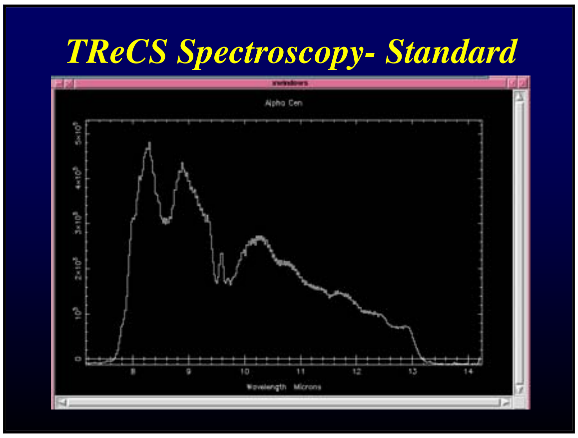

E
N
E
N
Circinus at 12um
May 6 2004

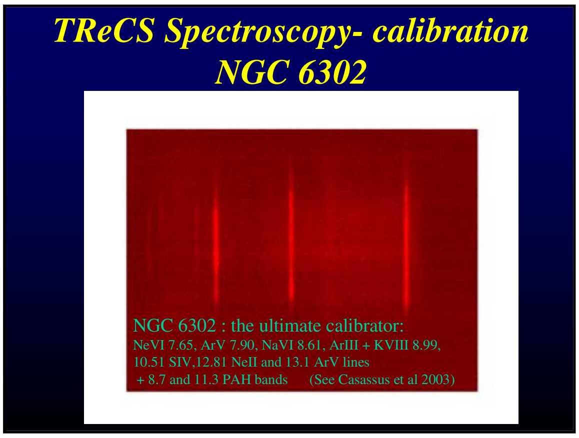

TReCS Data – Spectroscopic sky

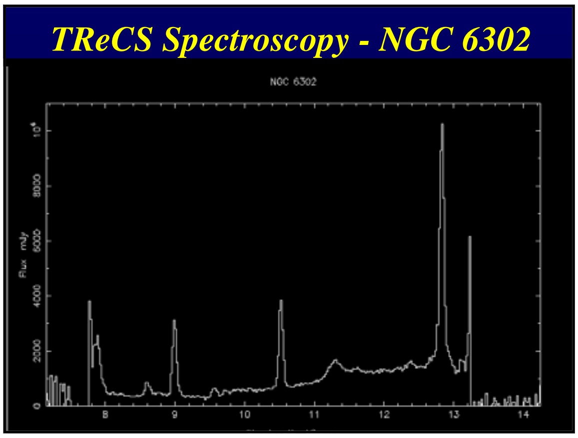

TReCS Spectroscopy- Object

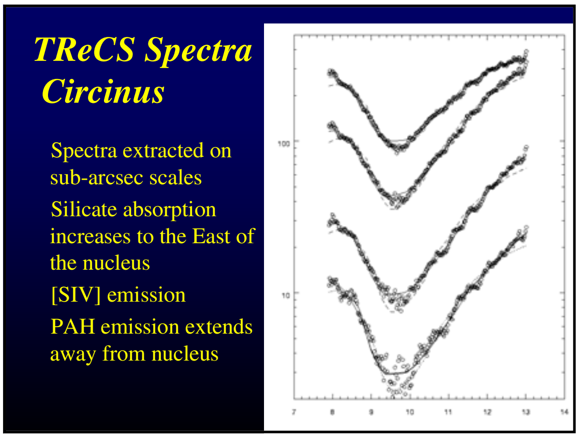

TReCS Spectroscopy- Object

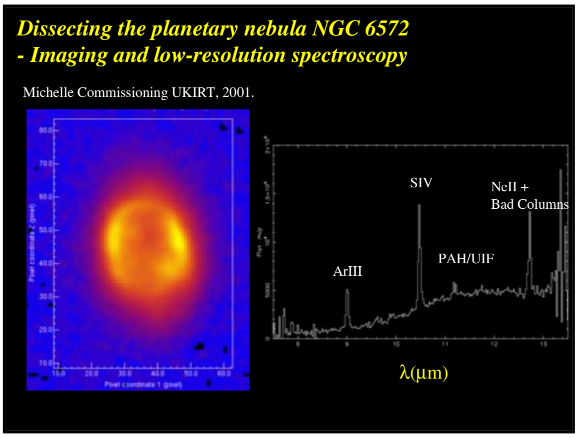

TReCS Spectroscopy- patched

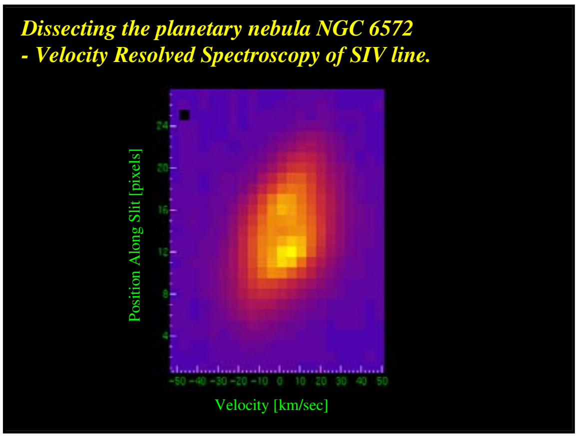

TReCS Spectroscopy- Standard
Alpha Cen
Wavelength Microns

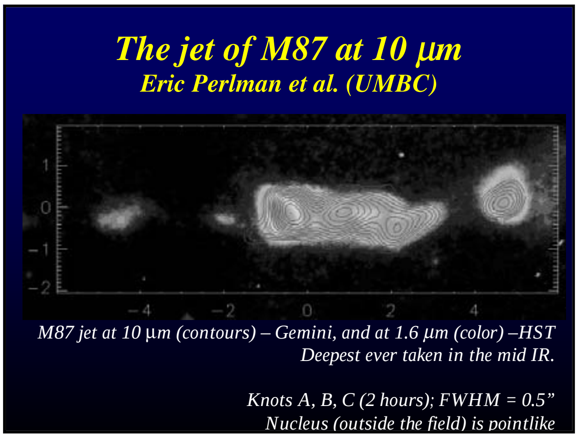

TReCS Spectroscopy- calibration
NGC 6302
NGC 6302 : the ultimate calibrator:
NeVI 7.65, ArV 7.90, NaVI 8.61, ArIII + KVIII 8.99,
10.51 SIV,12.81 NeII and 13.1 ArV lines
+ 8.7 and 11.3 PAH bands (See Casassus et al 2003)

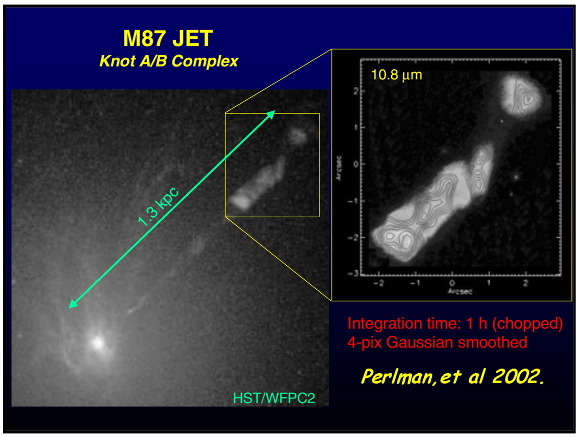

TReCS Spectroscopy - NGC 6302
NGC 6302

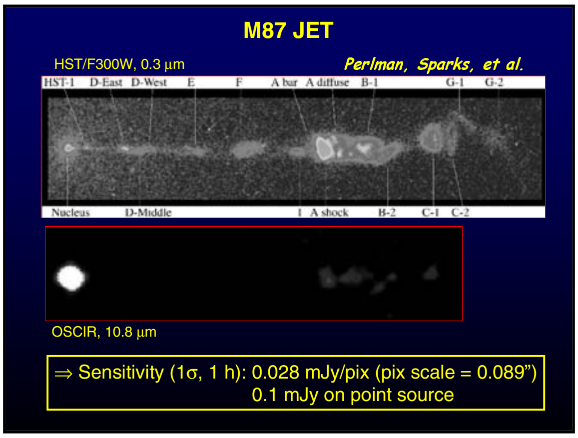

TReCS Spectra
Circinus
Spectra extracted on sub-arcsec scales
Silicate absorption increases to the East of the nucleus
[SIV] emission
PAH emission extends away from nucleus

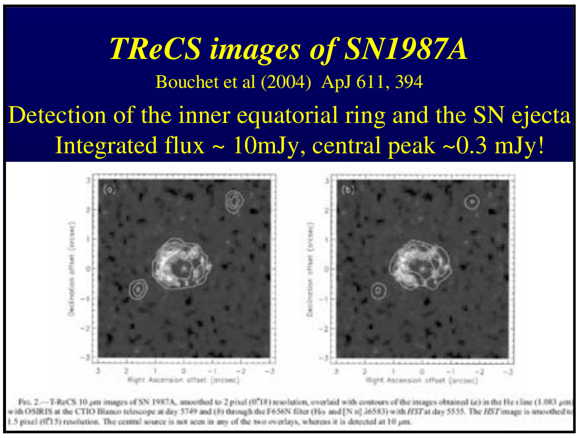

Dissecting the planetary nebula NGC 6572
- Imaging and low-resolution spectroscopy
Michelle Commissioning UKIRT, 2001.
SIV
NeII +
Bad Columns
ArIII
PAH/UIF
λ(µm)

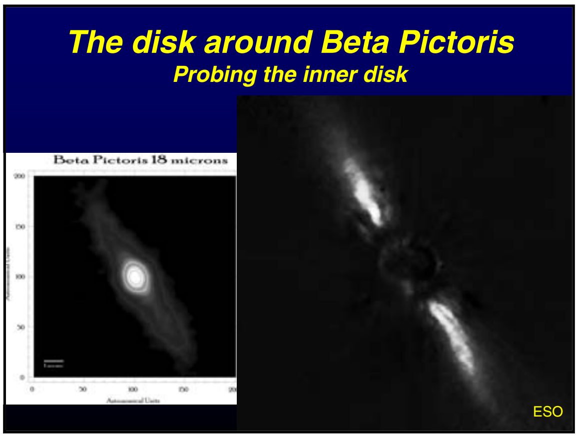

Dissecting the planetary nebula NGC 6572
- Velocity Resolved Spectroscopy of SIV line.
Position Along Slit [pixels]
Velocity [km/sec]


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
1.3 kpc
10.8 µm
HST/WFPC2
Integration time: 1 h (chopped)
4-pix Gaussian smoothed
Perlman, et al 2002.


M87 JET
HST/F300W, 0.3 µm
Perlman, Sparks, et al.
HST-1 D-East D-West E F A bar A diffuse B-1 G-1 G-2
Nucleus D-Middle I A shock B-2 C-1 C-2
OSCIR, 10.8 µm
⇒ Sensitivity (1σ, 1 h): 0.028 mJy/pix (pix scale = 0.089”)
0.1 mJy on point source


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!

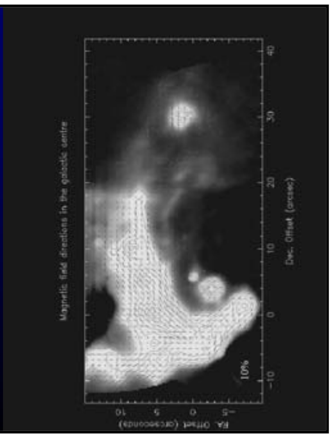

The disk around Beta Pictoris
Probing the inner disk
Beta Pictoris 18 microns
ESO

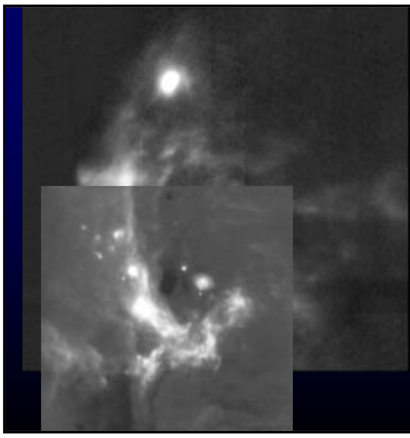
Potential for new modes.

Michelle has its own waveplate in the calibration unit for imaging and spectro-polarimetry

Dust grain alignments, magnetic field directions at subarcsec resolutions.

Dust grain properties





MIDI – High spatial resolution with the VLTI

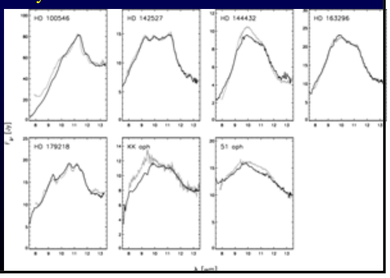
Interferometry on hundred metre baselines

Bright compact sources >1 Jy @ 10um

Spectral size information at R~ 30

HAeBe 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