

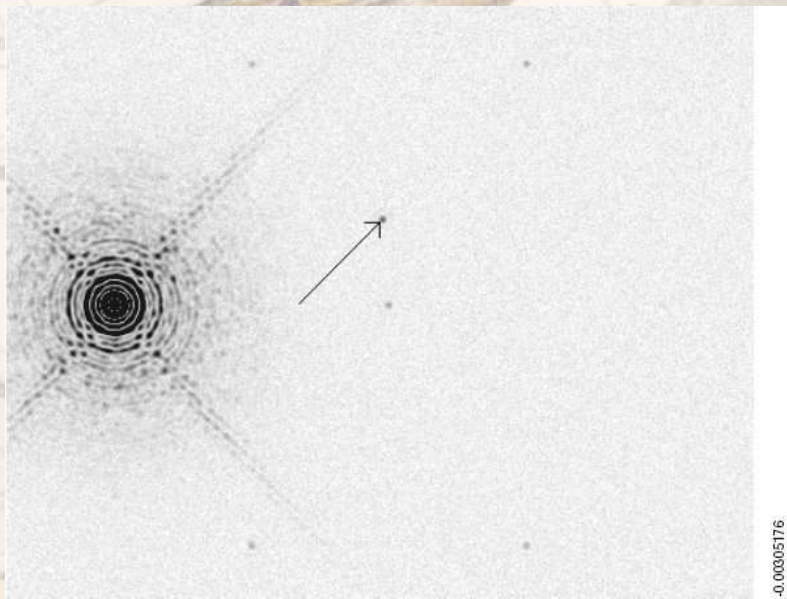


The Case of a Planetary Spectrograph for ELTs : NOCTUA

- Contrast Problem
- Analysis of Atmospheres of Extra-Solar Planets for Sure a “Killer Application” of ELTs
- Promising Spectral Features
- Biomarkers
- Resulting Requirements for Instrumentation
- What Could a Planetary Spectrograph Look Like
- CRIRES as a Preparatory Instrument
- Collaborators Florian Kerber and Bernard Delabre

A Planetary Spectrograph : the Next Logical Step ?

- continuing at the present rate, there will be 100s of extrasolar planets known when an OWL/ELT becomes fully operational:
- planets are being chased now or in the near future by:
 - radial velocity searches: e.g. HARPS and soon CRIRES
 - occultation studies: e.g. ESA's CoRoT mission
 - search for micro-lensing events
 - and more, especially when telescopes $> 8-10\text{m}$ become operational, e.g. EPICS (Kasper, this conference)

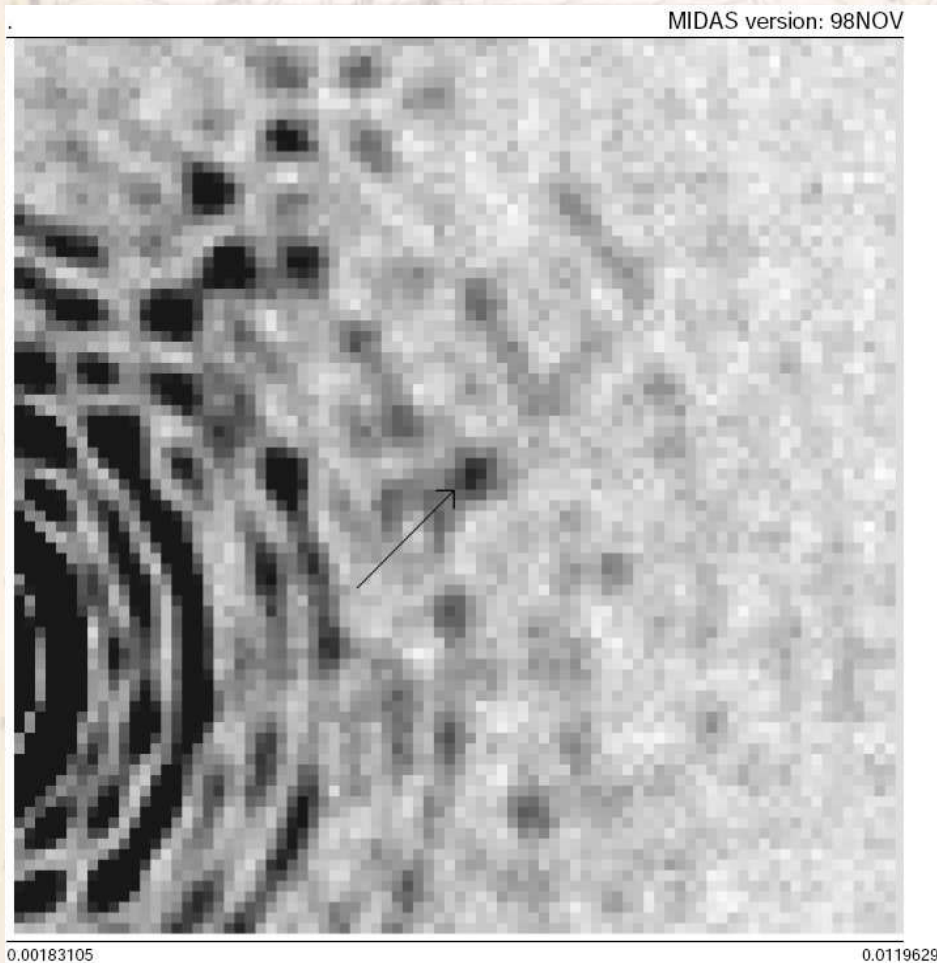


**e.g. Jupiters can “easily”
be imaged at 10/20 μm with
T-OWL (Lenzen, this conf.)**

**← simulation, Jupiter
around α -CenA at 20 μm
(Käufel and Monnet, 2000)**

Direct Imaging of Rocky Earth Like Planets

- feasible within few parsecs with an OWL/ELT :



“Earths” can “just” be imaged at 10/20 μm

- simulation, Earth around α -CenA at 20 μm (Käufli and Monnet, 2000)
- both a question of sensitivity and contrast (c.f. T-OWL study, R. Lenzen, this conf.)
- once found, there is a need to understand these planets

Planetary Atmospheres

- for the moment one needs to extrapolate from our Solar System
 - optically thick atmospheres: Jupiter, Saturn, Neptune & Uranus
 - optically thin atmospheres: Earth, Mars (Venus is an intermediate case)
 - Spectral Features:
vibrational rotational molecular lines:
 H_2O , CO_2 , CH_4 , NH_3 + many many others as exotic as GeH_4
(for recent reviews see the de Bergh and Lellouche, 2005 in proceedings of the ESO Workshop on High Resolution Infrared Spectroscopy in Astronomy)
 - Intrinsic line widths (integrated light!):
 - thermal broadening only: Venus, Stratosphere, 300-500m/s
 - pressure broadening : Venus, ~ 1km/s
 - $v \cdot \sin(i)$ – broadening : giant planets: 1-20 km/s
Earth, Mars 500-1000 m/s

The Infrared View

- Wien's law helps :

$$\lambda_{max} = \frac{2897.8 \mu m}{T [K]}$$

- Optimum Contrast Planet- Star :

$$\frac{F_{planet}}{F_{star}} \leq \left(\frac{r_{planet}}{r_{star}} \right)^2 \cdot \frac{T_{planet}}{T_{star}} \quad == \text{in Jeans limit} \quad (\lambda > 30\mu m)$$

- Brightness ratio of G2 type star vs. Earth and Jupiter like planets

$\lambda[\mu m]$	0.5	1.3	2.2	4	10	20	∞
$F_{Jupiter}/F_{Sun}$	4.3E-09	4.3E-09	4.3E-09	4.3E-09 (8.3E-15)	4.5E-08	5.3E-06	2.3E-04
F_{Earth}/F_{Sun}	2.2E-11	2.2E-11 (1.3E-20)	2.2E-11 (2.8E-14)	3.0E-10	1.7E-07	1.0E-06	4.3E-06

black: planet in reflected starlight; red: planet in thermal emission (LTE)

=> if at all, extrasolar planets are detectable in the IR

- additional aspects:

- stray-light problems scale with $(1/\lambda) - (1/\lambda)^4$
- image quality of ground-based telescopes are a trade-off between diffraction limit and atmospheric distortions: at 2 μm image quality may approach 5 mas

- example for a potential feature: CH_4

(Deming et al. 2000);
was searched for in
the hot Jupiter type
companion of τ Bootis
by Wiedemann et.
al 2001

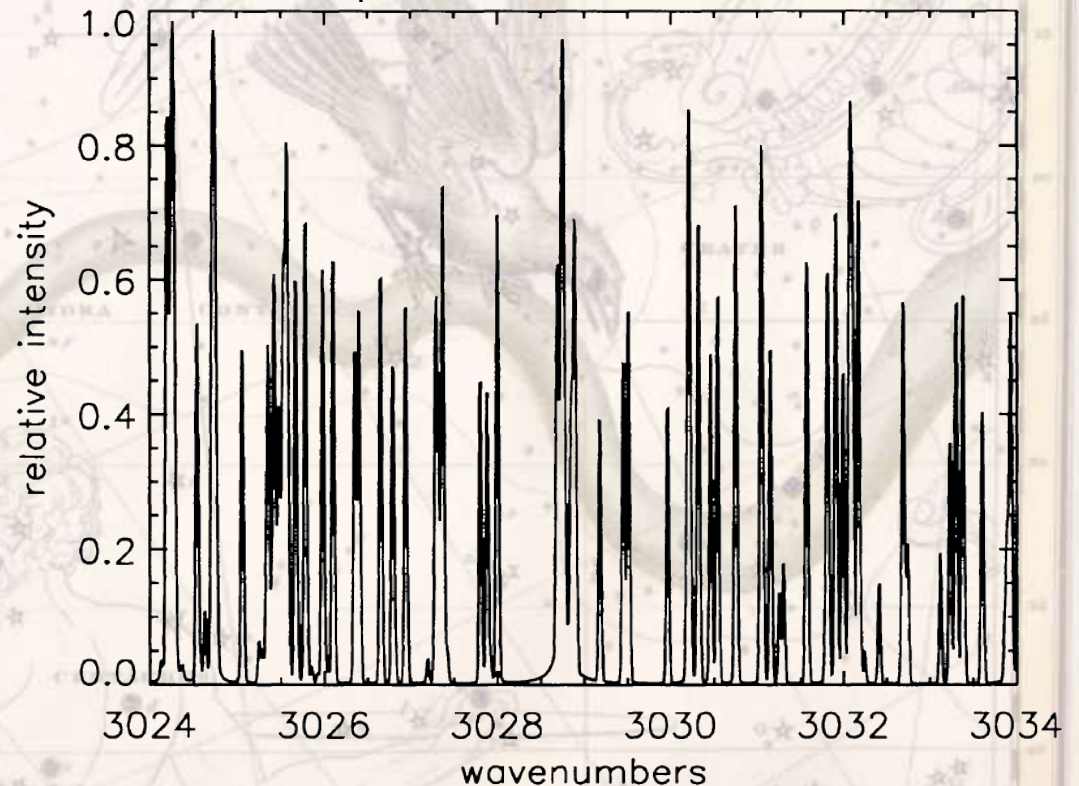


Figure 2. Spectrum of methane at 1200 Kelvins.

Spectroscopic Features from Cooler Earth Like Planets

- example / most favoured species: O_3 , CO_2 or H_2O
but
- these species can only be observed from space (e.g. DARWIN)

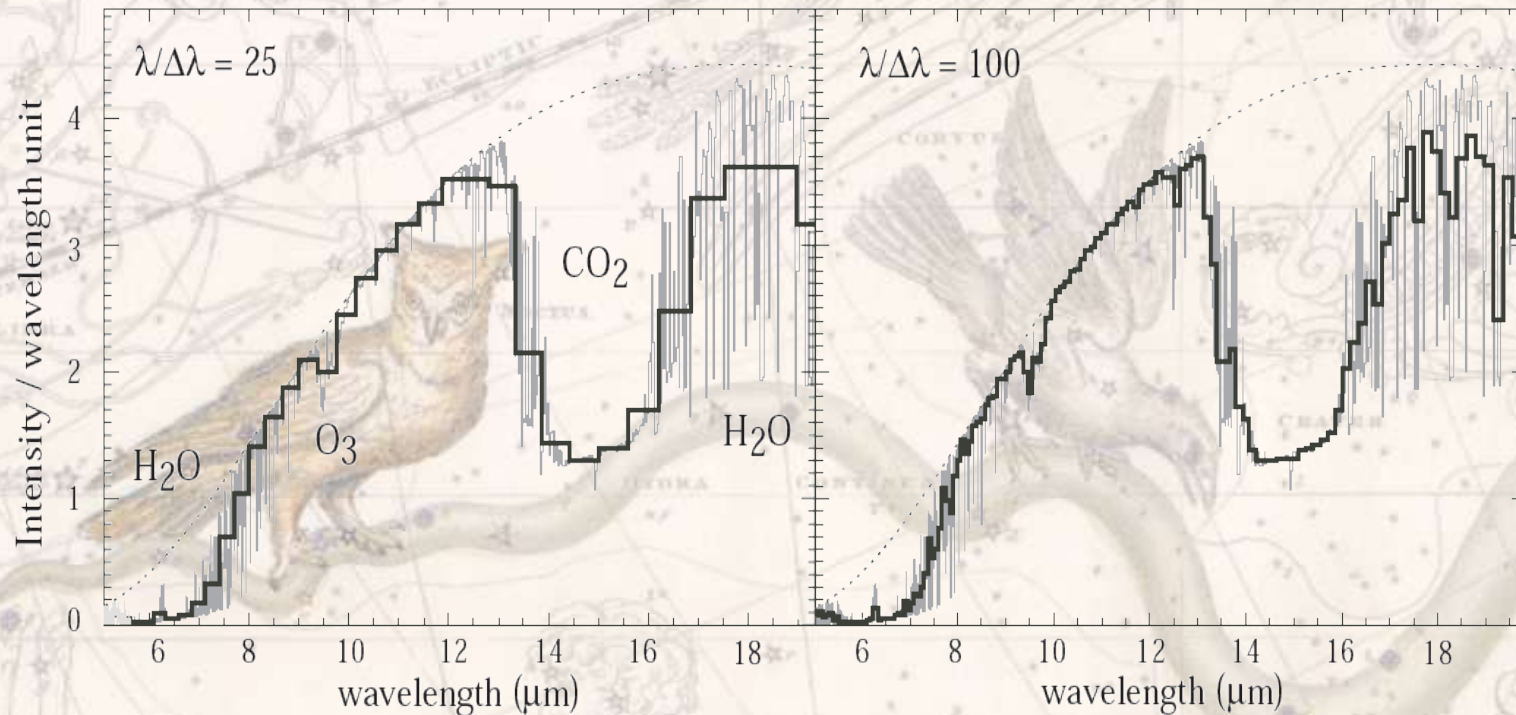


Fig. 14. Case G: IR Darwin spectrum simulated for a humid atmosphere (1 bar N_2 , 0.1% H_2O) with constant H_2O influx and little CO_2 (0.03%). The O_3 line is barely detectable at present ($R = 25$, left) and improved ($R = 100$, right) Darwin resolution. Despite the presence of CO_2 and H_2O line, the risk to detect such case as a “false positive” is marginal.

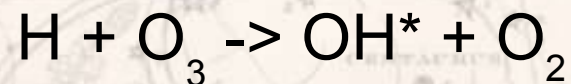
- sample spectra from Selsis et al. 2002

Another Idea for Spectroscopy of Earth Like Planets

- **NOCTUA: Novel Oxxygen Census Testing Unknown Atmospheres**

ideal spectral feature should be:

- bright => non LTE population necessary
 - in a clean infrared window
 - should have narrow lines:
then a real high resolution spectrograph can be employed to “dilute” the stellar continuum
 - feature should be a potential bio-marker
- radiative non-LTE features are known (e.g. CO₂ on Mars and Venus) but do not produce really strong lines
 - proposal is to use the OH airglow:
produced by the chemical reaction



here on Earth, in ~ 90km altitude

OH – airglow spectra

1148

P. Rousselot et al.: Night-sky spectral atlas of OH emission lines

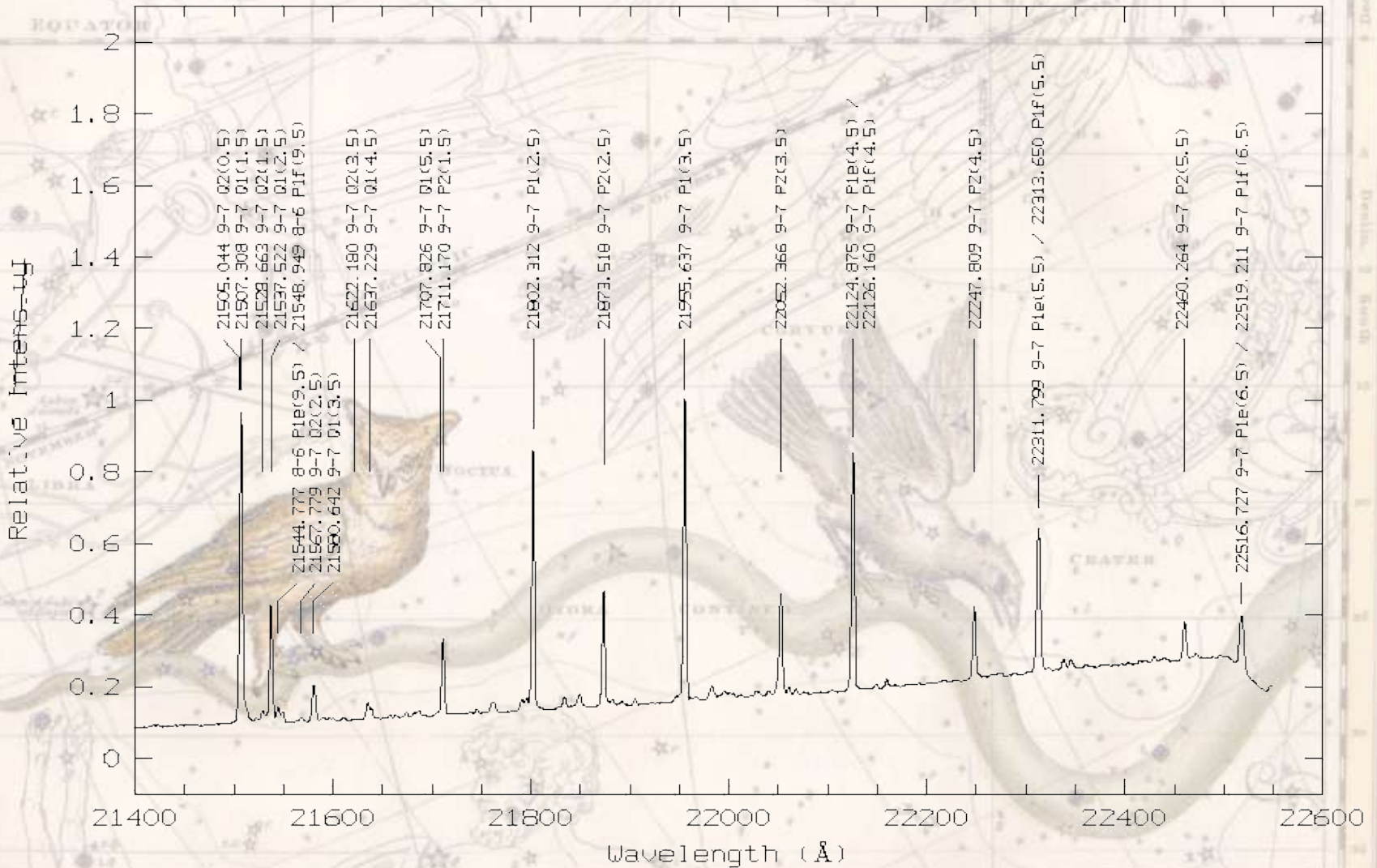


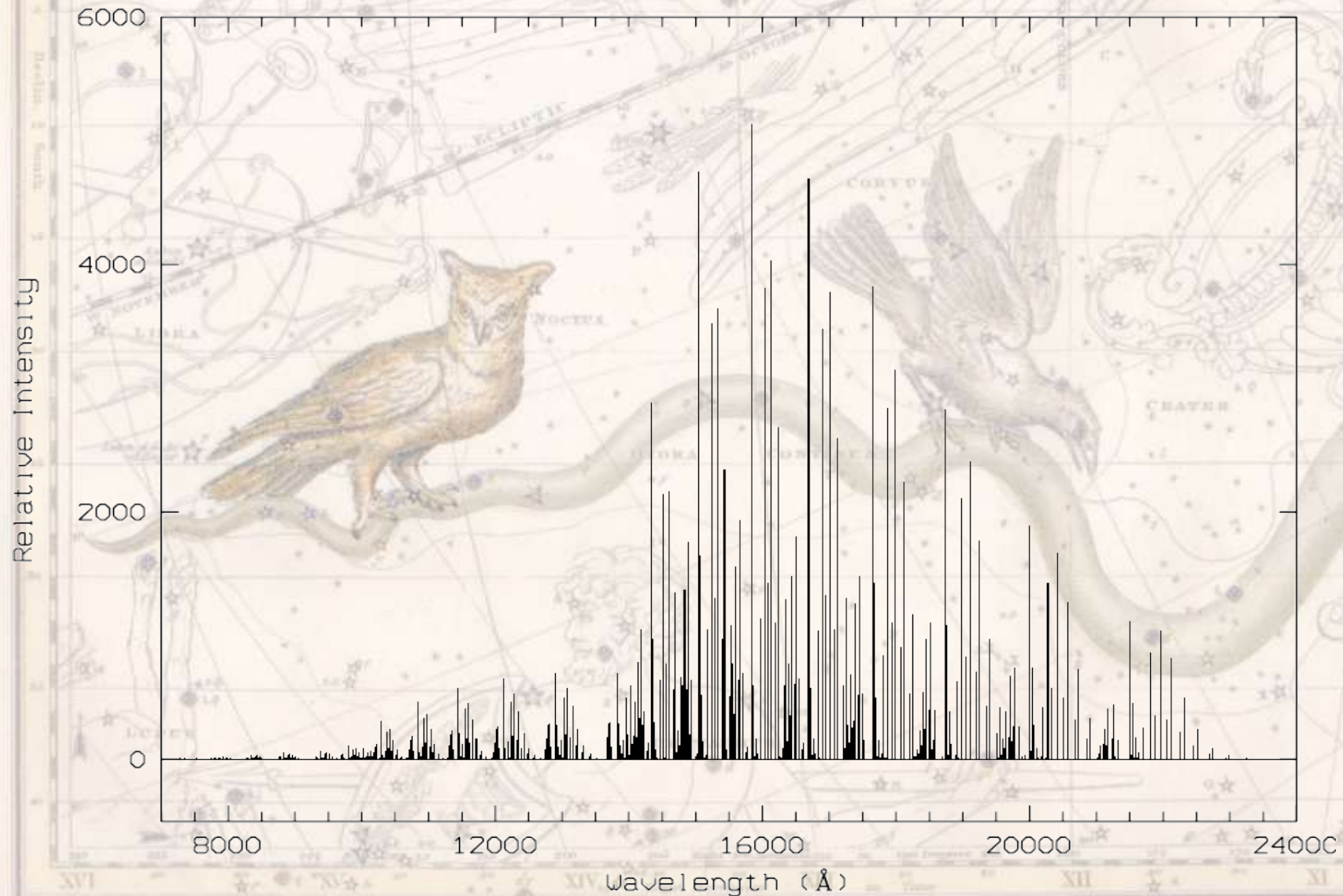
Fig. 23. Cerro Paranal night-sky emission-line spectrum, range 21400–22550 Å. The wavelengths are given in vacuum.

- ISAAC sample spectrum, unresolved,
- at $\lambda / \Delta\lambda \sim 10^6$ the lines will appear 30 times brighter

Band Structure of the OH-Meinel Bands

- precise frequencies from fully resolved FTS-lab spectra exist (Abrams et al. 1994)

P. Rousselot et al.: Night-sky spectral atlas of OH emission



Requirements for the NOCTUA Spectrograph

- primary wavelength range: 1400 – 2000 nm
- secondary wavelength ranges: 3000 – 4000 nm
1900 – 2500 nm
- nominal spectral resolution: 300 m/s [$\lambda / \Delta\lambda \sim 10^6$]
- 3 pix sampling as Nyquist – sampling may not be enough
=> 10^6 pixels effective in dispersion direction (=20m !!)
- and then the usual stuff:
 - maximum throughput
 - low stray light
 - high spectral purity
 - optics diffraction limited
 - acceptable stability: < 10 m/s
 - detector noise: $\sim 0 e^-$
 - dark current: $\sim 0 e^- / s$
 - perfect AO, > 50% Strehl with efficient coronagraphy

Resulting Challenges for the NOCTUA Spectrograph

- detector for cross-dispersed spectrograph:
 - mosaic of 1 x 40 or 2 x 20 4k x 4k detectors
 - spectrum recorded in ~12 - 24 orders
 - => slit-length ~ 600 pix @ 3mas / pix (or 1.8 arcsec total)
 - this appears to be in the extrapolation regime of today's devices, including controllers (~ 10 times VISTA-IRACE)
- size of focal plane: ~ 80 x 3200 mm²
 - area is not too far from present Wide Field CCD Imagers

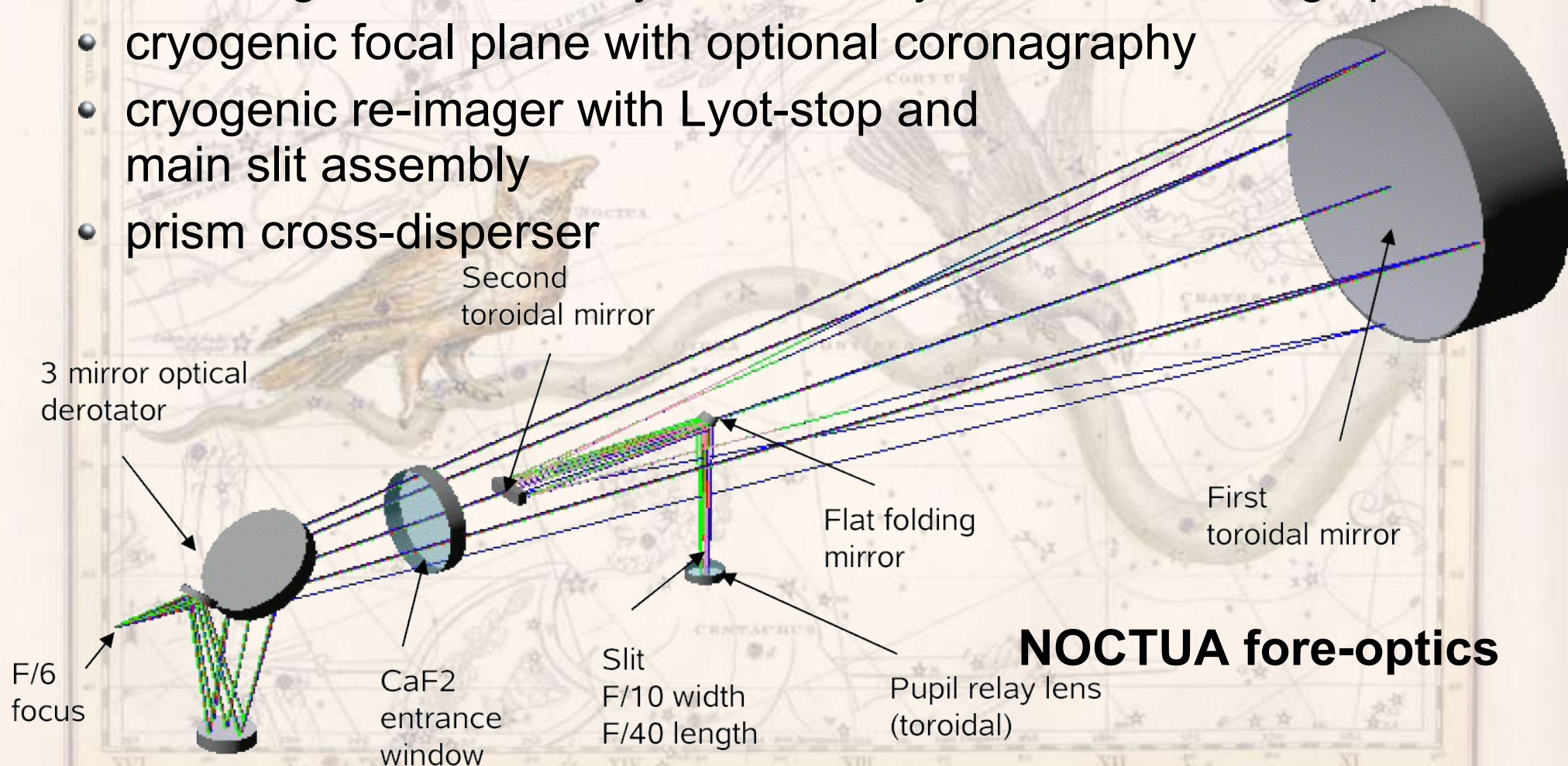
BUT

- for straylight, throughput and spectral purity reasons only a single pass grating can be considered:
 - ==> the grating needs to be 4m long
 - collimator f#10 / 40 to match 20 μ m pixels
 - with an R4 Echelle one needs 10m focal length !

==> NOCTUA will be a BIG instrument

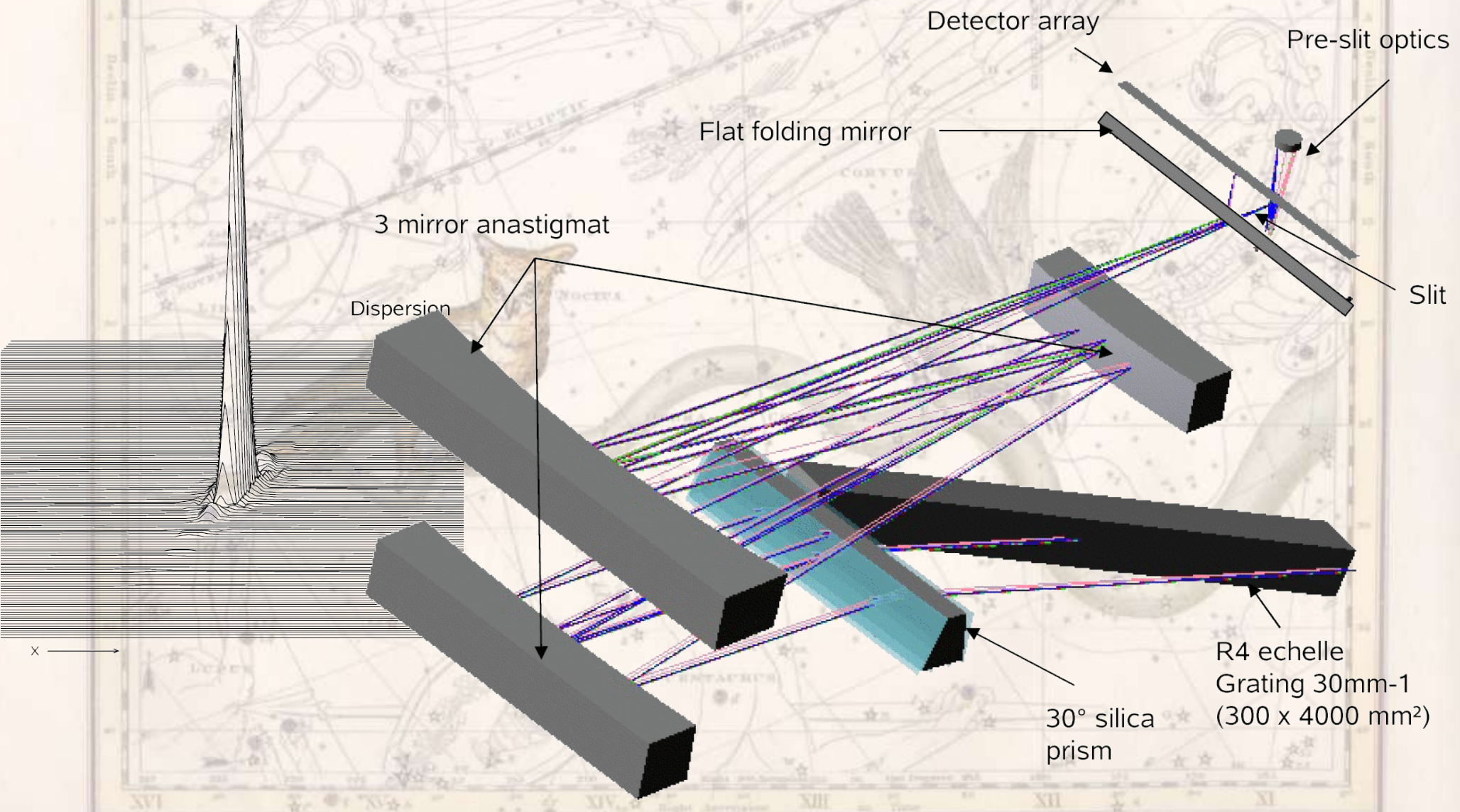
NOCTUA Conceptual Design:

- scaled up version of VLT-CRIRES:
 - stationary at Nasmyth preferred but fiber feed possible
 - UVES/CRIRES type field de-rotator (straight copy?!)
 - natural guide star AO system: clearly more than enough photons
 - cryogenic focal plane with optional coronagraphy
 - cryogenic re-imager with Lyot-stop and main slit assembly
 - prism cross-disperser



NOCTUA Main Spectrograph Conceptual Design:

- diffraction limited PSF (anamorphic!)



Sensitivity Issues:

- based on OH-IR emission atlas and the expected sensitivity for CRIRES one can assume, that for an Earth-like planet, NOCTUA@OWL can detect

one OH-line with $\sim 1 \sigma / h$

- there are ~ 20 strong and 100s of weaker lines
=> detection per se with a 100m telescope feasible when planet in quadrature

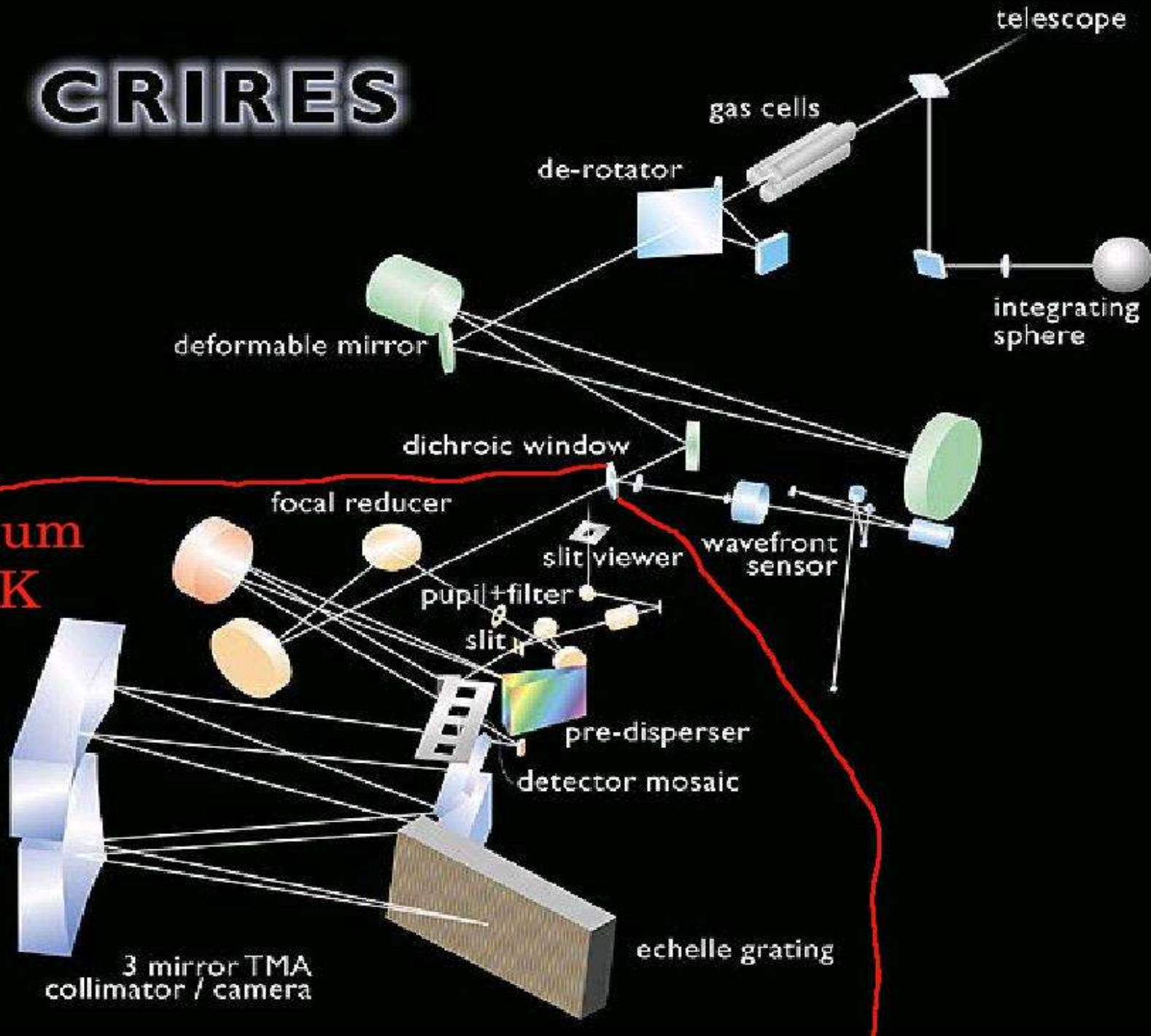
but

- telescope should not be much smaller than 100m
- problem is contrast to central star of extrasolar planetary system, as usual

therefore, CRIRES shall be used as a test-bed

CRIRES

vacuum
~65 K



CRIRES Main Characteristics:

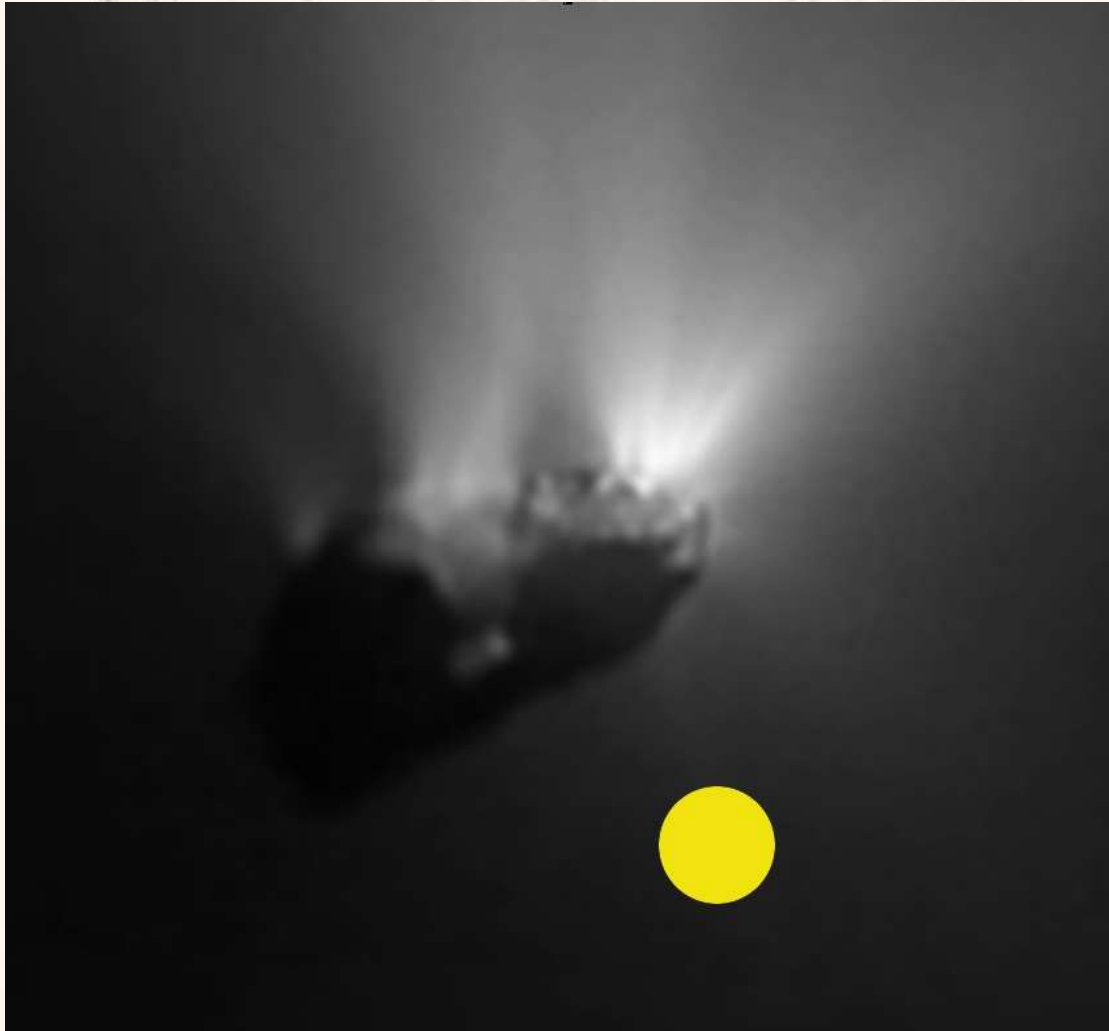
- **wavelength coverage:** $\lambda \sim 0.95 - 5.2 \mu\text{m}$
- **spectral resolution:** $\lambda / \Delta\lambda \approx 10^5$ or $\Delta v \approx 3 \text{ km/s}$
2 pixel Nyquist sampling; pixel scale $0.1''/\text{pix}$
- **array detector mosaic:**
4 x 1024 x 512 Aladdin III InSb mosaic
☞ instantaneous λ - coverage $> 2.0 \%$
- **infrared slit viewer** (Aladdin III) with J, H & K-filters
- **precision** for calibration and stability $\sim 75 \text{ m/s}$
i.e. $1/20^{\text{th}}$ of a pixel or 5 mas tracking error
☞ gas cells for high precision radial velocity work
- curvature sensing **Adaptive Optics**
☞ $0.2''$ spatial resolution for $40''$ slit
- Piezo-electric actuator in pre-disperser collimator for vernier adjustment of spectrum on detector

CRIRES: Preparatory Activities for OWL

- new atlas of the telluric OH air-glow:
 - ISAAC did not resolve various lines
- measuring the telluric OH-airglow in reflection from the Moon
 - allows for some “proof of principle”:
 - strong direct telluric background and solar background
 - synoptic study of individual line strengths from the illuminated side of the Earth
- scanning Solar System planetary atmospheres for OH-airglow to establish uniqueness of feature
- measuring the Solar OH emission in reflection from asteroids
- searching for signatures from the atmospheres of “hot Jupiters”
- establishing ThAr as reference beyond $1 \mu\text{m}$

NOCTUA in Our Solar System:

- Comet research as one example:



line width in cometary gas outflows $< 1\text{km/s}$:

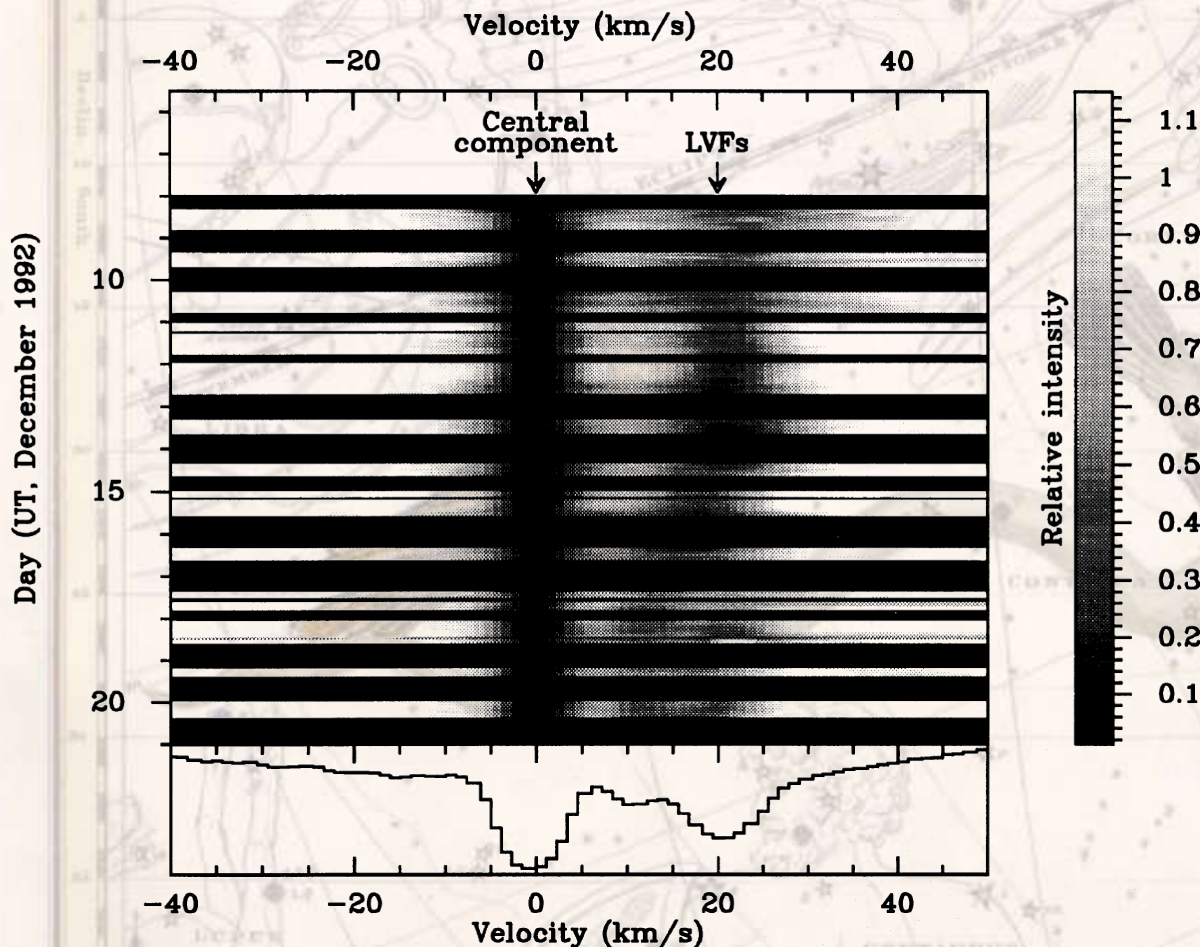
- many molecular species known with transitions between $1\text{-}5\mu\text{m}$
- spatial resolution sufficient to see right into the base of cometary active areas
- for 9P/Tempel 1, Deep Impact the impact area would have been resolved by NOCTUA/OWL!

↑ Giotto image of comet Halley with OWL/NOCTUA PSF (@1 AU)

NOCTUA/OWL and Falling Evaporating Bodies (FEBs)

- only known example so far: β - Pictoris

A.-M. Lagrange et al.: The β Pictoris circumstellar disk. XXI



red-shifted narrow absorption interpreted as evaporating comets

- $\lambda / \Delta\lambda \sim 10^5$ not enough to resolve an “evaporating comet”
- IR allows to extend study e.g. to CH_2O
=> excludes rocky FEBs
- OWL sensitivity
=> representative samples can be studied

Other Potential Astrophysical Applications:

- Asteroseismology: Infrared biased to Chromospheres:
=> new discoveries
see e.g. Deming et al, 1986
- Interstellar Medium and Star Formation

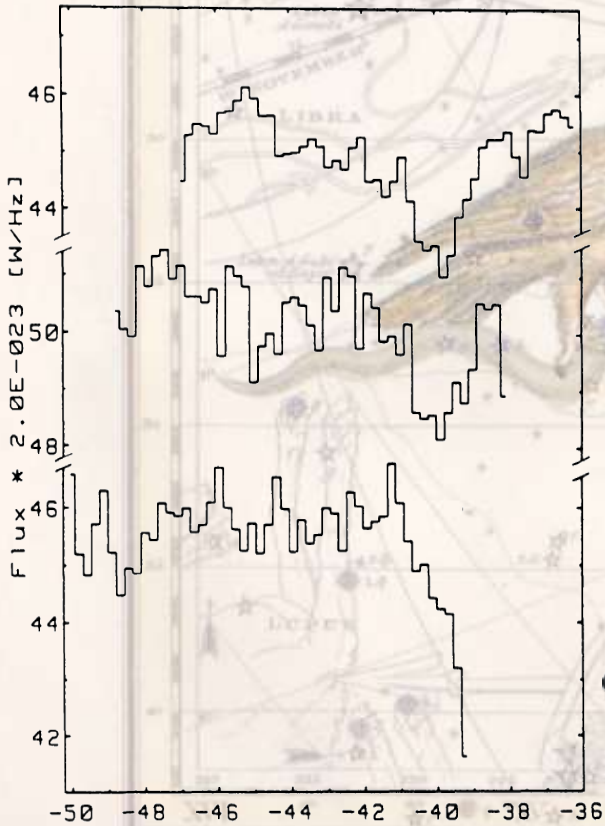


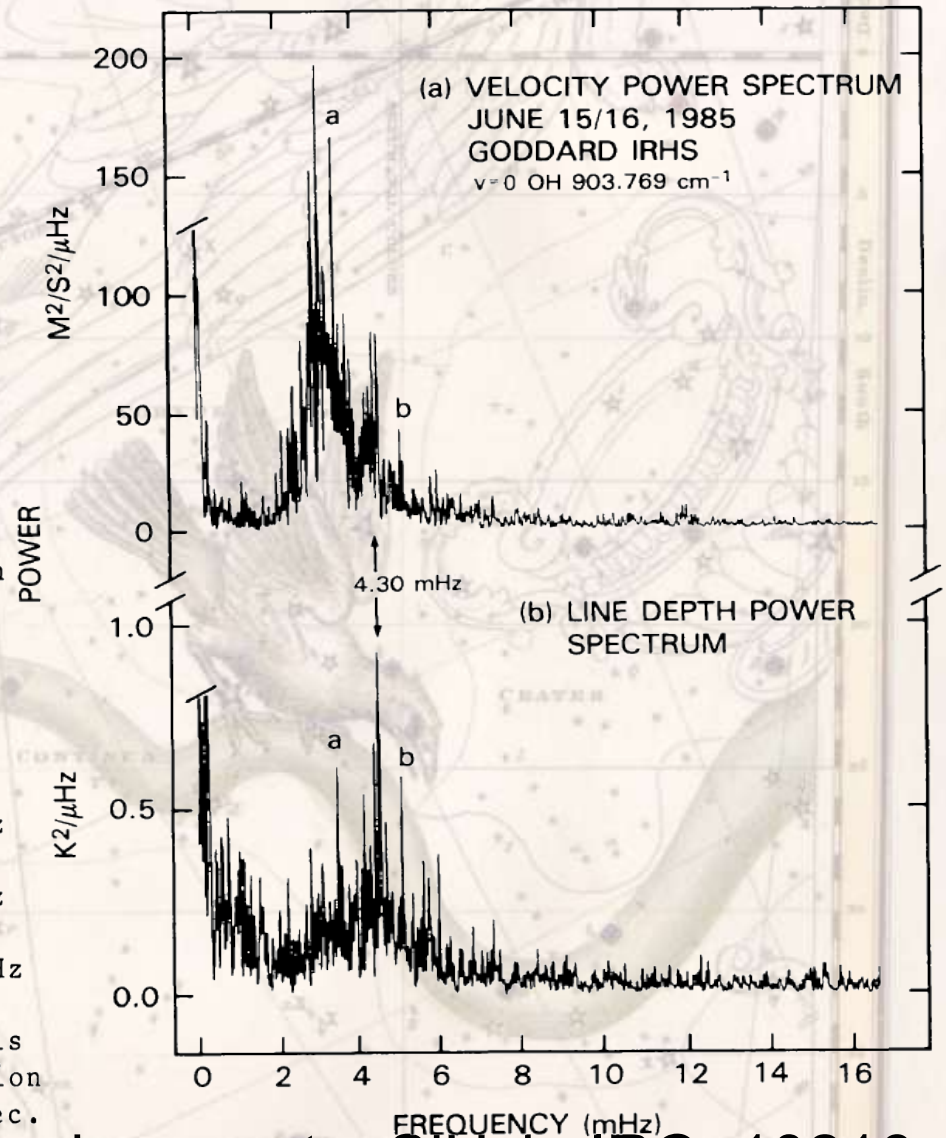
Fig. 1: Silane absorption lines in IRC 10216

Transition, frequency ν , equivalent width W :

- P⁺(4)F₂ ← F₁:
26939885±3 MHz, 15±3 MHz
- Q^o(8)F₂ ← F₁:
27043262±10 MHz, 7±2 MHz
- P⁺(5)F₂ ← F₁:
26835800±200 MHz, 8±4 MHz

The spectral resolution is 0.2 km/sec, the integration time per spectrum 2000 sec.

- circumstellar environments: SiH₄ in IRC+10216
with OWL spectrally and spatially resolved!





The Case of a Planetary Spectrograph for ELTs : NOCTUA

- Analysis of Atmospheres of Extra-Solar Planets for Sure Are a “Killer Application” of ELTs !
- Contrast Problem: tough, but NOCTUA is a good approach
- Promising Spectral Features and Biomarkers: exist
- CRIRES as a Preparatory Instrument will soon be commissioned: --> stay tuned
- NOCTUA has also a broader relevance for astronomy sub-Doppler spectroscopy, a field so far overlooked: *“you can't be too rich and you can't be too thin and you can't have too much spectral resolution” Dan Jaffe*
- Collaborators: welcome, to make this a real project