Spectrum Reduction

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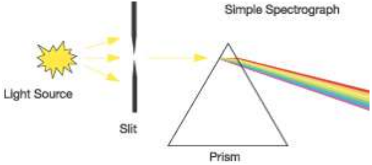
Outline

- What is a spectrograph?
- spectrum reduction

What is a spectrograph?

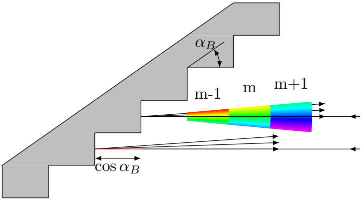
- dispersive element
  - grating
  - prism
  - grism
- camera + detector



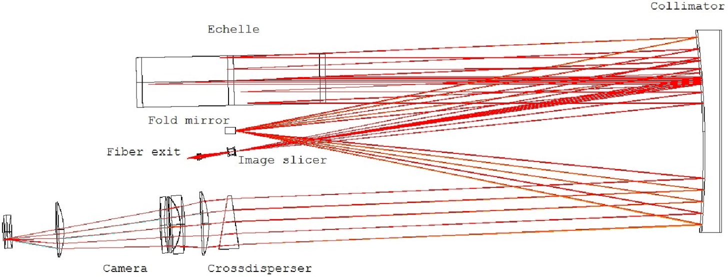
- characteristics and types of spectrographs
  - resolution: high / low
  - slit (CRIRES, UVES) / fibre-fed (HARPS, CARMENES)
  - layout (echelle)
  - single-object / multi-object / integral field spectrographs (IFS) (e.g. SINFONI)

CARMENES – Layout

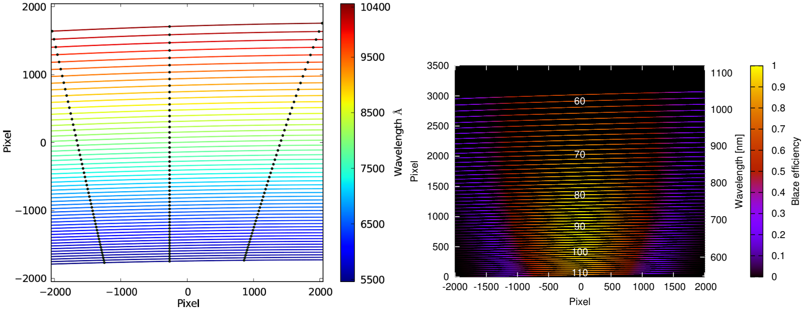
- fibre-fed echelle spectrograph
- echelle diffraction grating
- cross-disperser (grism)
- triple pass of the collimator



blaze grating (echelle)



CARMENES – Spectral Format



CARMENES echelle format (VIS)

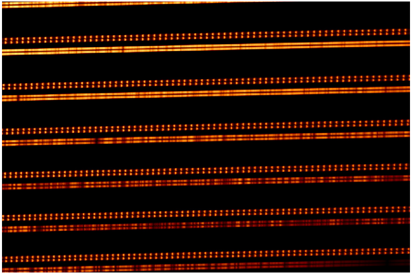
CARMENES – Design Parameters

	VIS	NIR
$\Delta\lambda$	530-1050 nm	950-1700 nm
$R=\lambda/\Delta\lambda$	80,000	85,000
Fibre size	1.50 arcsec	1.65 arcsec
Grating	2 x R4 (31.6 mm^{-1})	2 x R4 (31.6 mm^{-1})
Cross disperser	grism	grism
Detector	e2v 231-84 (4k x 4k)	2 x Hawaii-2RG (4k x 2k)

- pressure and temperature stabilised (vacuum tank)
- two fibres
  - fibre A: science object
  - fibre B: simulatenous calibration (RV drift or sky)

Raw spectrum

- spectrograph images the slit to wavelength dependent positions



- Data reduction: How do we get the spectrum?

Reduction software

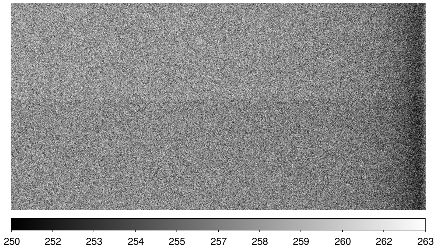
- IDL (REDUCE, Piskunov & Valenti, 2002)
- IRAF
  http://iraf.noao.edu/tutorials/doecslit/doecslitgif.html
- Python
- Pyraf
- ESO-MIDAS
- instrument specific pipelines

Data Reduction

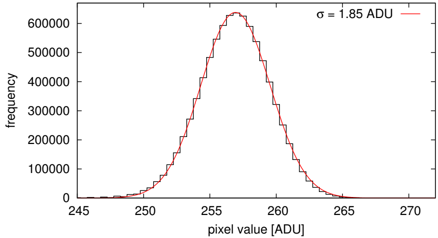
- bias correction
- flat fielding
- stray light subtraction
- spectrum extraction
- wavelength calibration
- order merging
- flux calibration

Bias correction

- Bias = electronic offset (amplifier)
- bias images:
  - exposure time = 0s
  - regular calibration
  - mean bias level
  - higher order systematics
  - readout noise
- master bias = average of bias images
- subtract master-bias
- measure readout noise from the count dispersion (histogram)

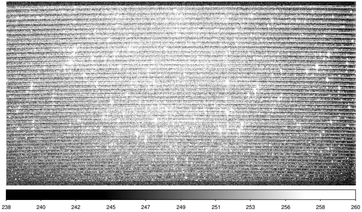


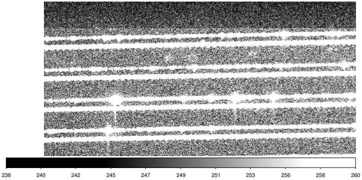
master bias (HARPS blue)



read-out noise

Bias correction



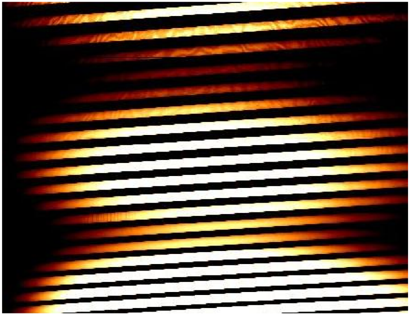


HARPS blue CCD

- measure mean bias level in science observations from pre-/overscan region (amplifier zero point correction)
- subtract mean (column) bias

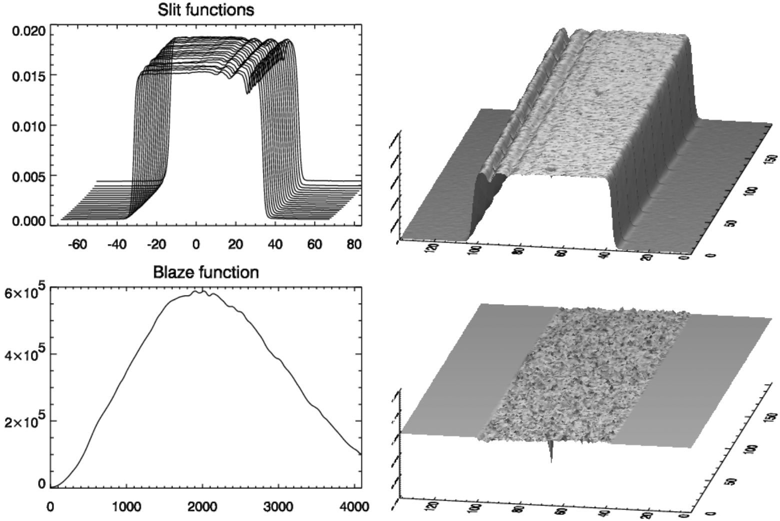
Flat field

- flat lamp: featureless, smooth spectrum
- multiplicative effects
  - pixel-to-pixel variations (pixel size and efficiency)
  - fringing (interference pattern)
  - blaze function (echelle grating)
  - wavelength dependent efficiency of spectrograph (optics + detector)
  - dust
- types:
  - sky flat in the twilight (telluric absorption)
  - dome flat
  - internal flat
- master flat = average of flat frames



HET HRS flat image

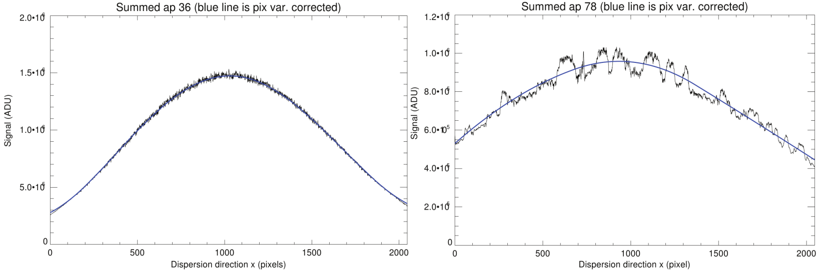
Flat field



UVES (Piskunov & Valenti, 2002)

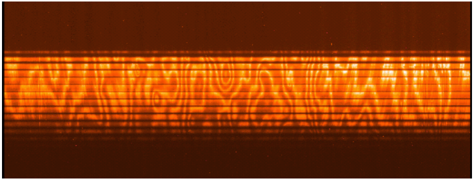
- creation of a normalised flat-field (decomposition)
- set low S/N regions to 1 (noise > pixel variations)
- divide by the normalised flat-field

Flat field



Buchhave (2010)
TRES spectrograph

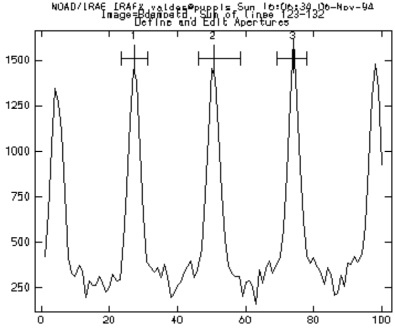
- fringing in the red order



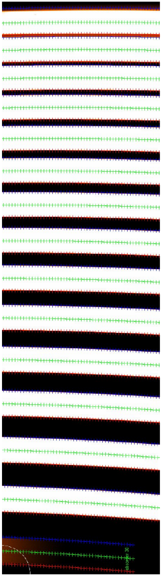
fringing in the CES spectrograph

Order and Aperture definition

- identify location and width of the spectrum (and background)
- order tracing
  $y_{\rm cen} = f(x, o)$

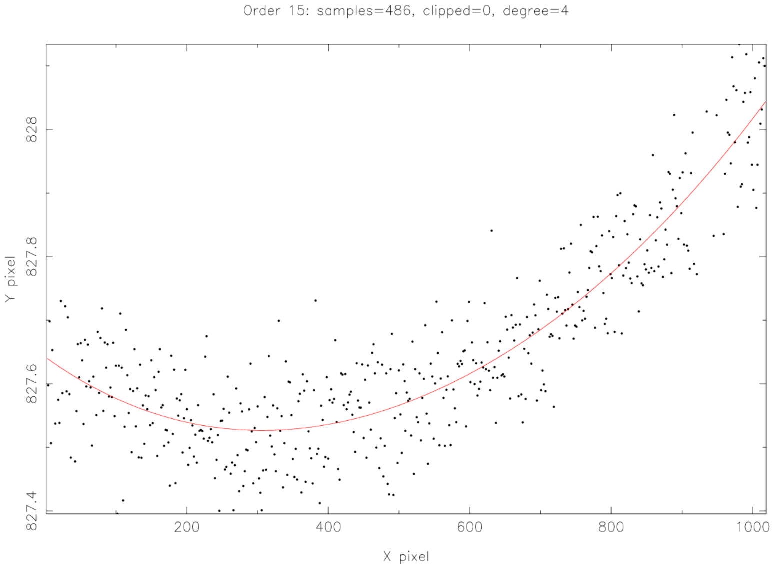


aperture defintion in IRAF



Modigliani (et al. 2012), X-Shooter

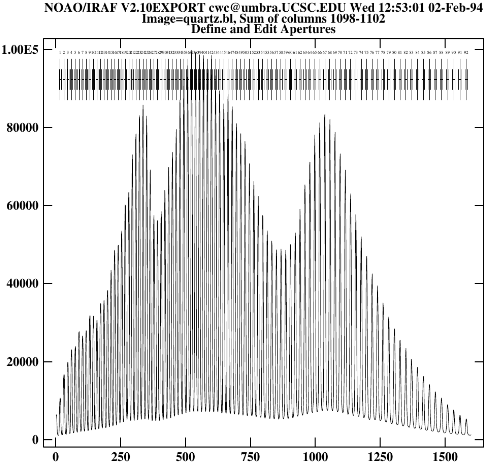
Order and Aperture definition



(Clayton, 1996)

Stray light correction

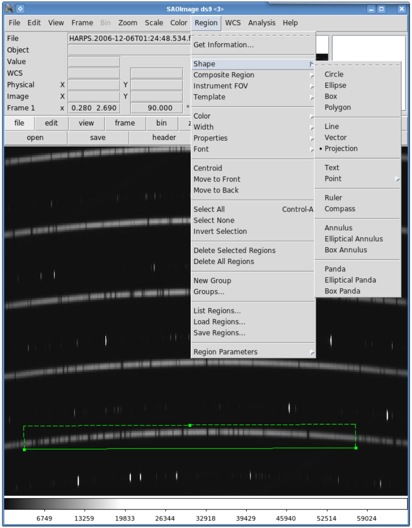
- global stray light (imperfection of the grating)
- local: inter-order/fibre crosstalk
- removal: polynomial/spline fit to the background regions and interpolation across the aperture

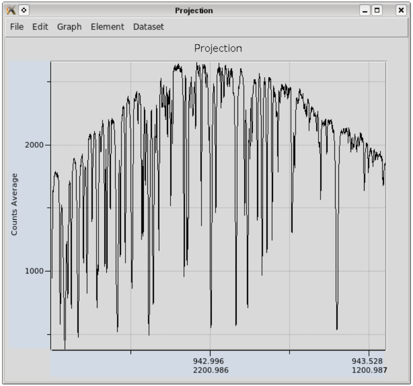


(Churchill, 1995)

Extraction

- Quick look extraction with SAOImage ds9



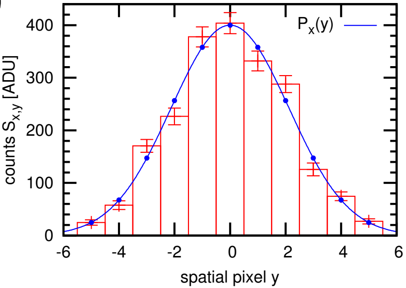


Linear Extraction

- sum the raw pixel flux across the column (within the extraction width) $s_x = \sum_y S_{x,y}$
- simple
- s_x has not minimal variance
- extraction width?
  - too large: adding read-out noise from regions with low/no signal
  - too small: loosing signal

Optimal Extraction

- weighted extraction (Horne, 1986)
- $s_x = \frac{\sum_y \sigma_{x,y}^{-2} p_{x,y} S_{x,y}}{\sum_y \sigma_{x,y}^{-2} p_{x,y}^2}$
- two weighting factors:
  - $p_{x,y}$ – profile value
    fractional flux
    normalised to unity
    $\sum_y p_{x,y} = 1$
  - $\frac{1}{\sigma_{x,y}^2}$ – (inverse) pixel noise
    read-out noise + photon noise
    $$\sigma_{x,y}^2 = \sigma_{\mathrm{rn}}^2 + \sigma_{\mathrm{ph}}^2$$



- equivalent to scaling of (1D) spatial profiles $p_{x,y}$
- s_x (the intensity) is the best scaling factor
- s_x is unbiased (i.e. the extracted values are on average the true values; if the spatial profile is a good model)
- s_x has minimal variance

Optimal Extraction

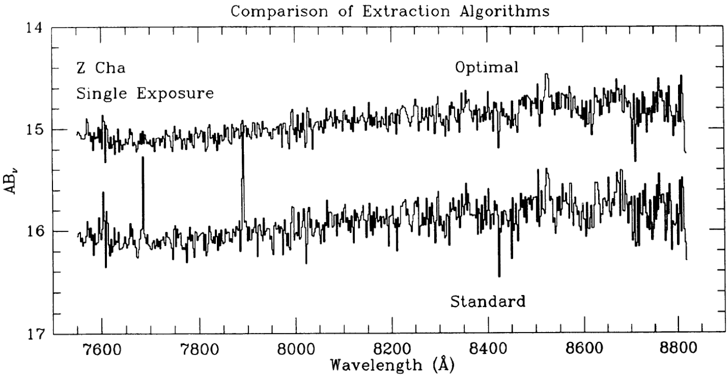
- case photon-noise only:
  - estimated photon-noise: $\sigma_{x,y} = \sqrt{gS_{x,y}}$
    (gain g: conversion factor between photon counts and digital counts)
  - predicted pixel flux: $S_{x,y} = p_{x,y} s_x$
  - estimated photon-noise: $\sigma^2_{x,y} = g p_{x,y} s_x$

$$s_x = \frac{\sum_y \sigma^{-2}_{x,y} p_{x,y} S_{x,y}}{\sum_y \sigma^{-2}_{x,y} p^2_{x,y}} = \frac{\sum_y S_{x,y}}{\sum_y p_{x,y}} = \sum_y S_{x,y}$$

  i.e. linear extraction

- same performance for high signal-to-noise
- better performance for low signal-to-noise
- in wings always low signal-to-noise
  extraction width not so important

Optimal Extraction

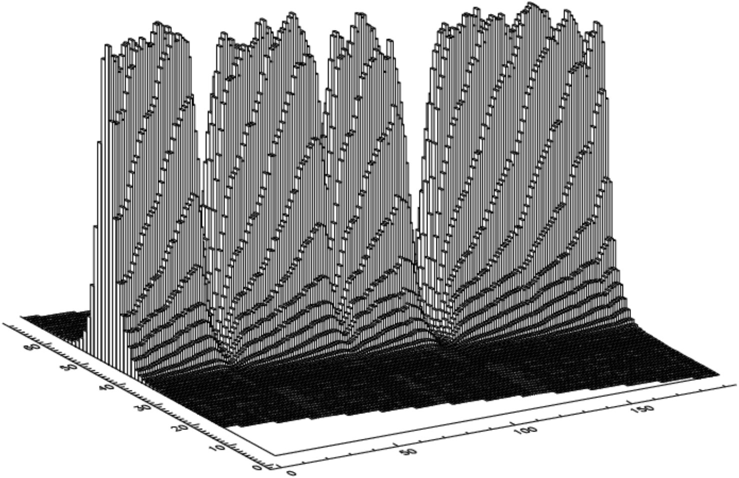


Optimal Extraction

- How do we get the cross-section $p_{x,y}$?
  - a. define an analytic function (e.g. Gaussian)
  - b. from a reference object (e.g. flat field)
  - c. from the observed object itself
- many algorithms

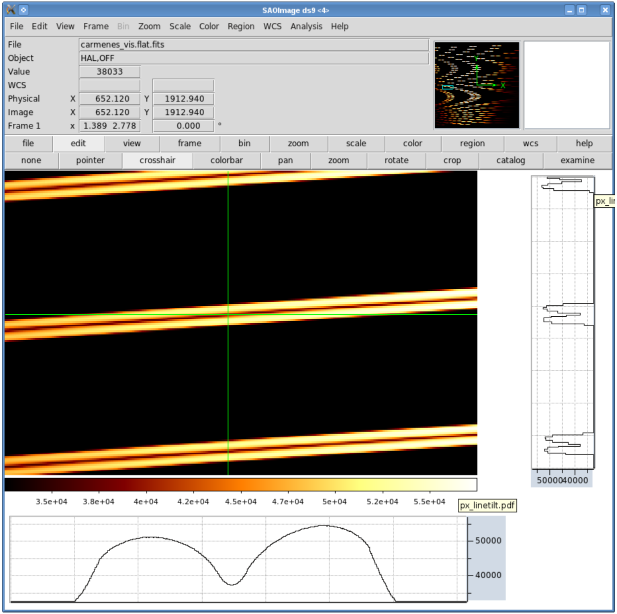
Reference	Cross-section model	comment
Hewett et al. (1985)	average along dispersion	assumes no order tilt
Horne (1986); Robertson (1986)	polynomials along dispersion	assumes small order tilt
Urry & Reichert (1988)	Gaussian function	
Marsh (1989)	coupled polynomials along dispersion	employs spatial subpixel grid
Piskunov & Valenti (2002)	penalised splines	employs spatial subpixel grid
this work	(master flat)	requires stabilised spectrograph

Optimal Extraction



(Piskunov & Valenti, 2002)

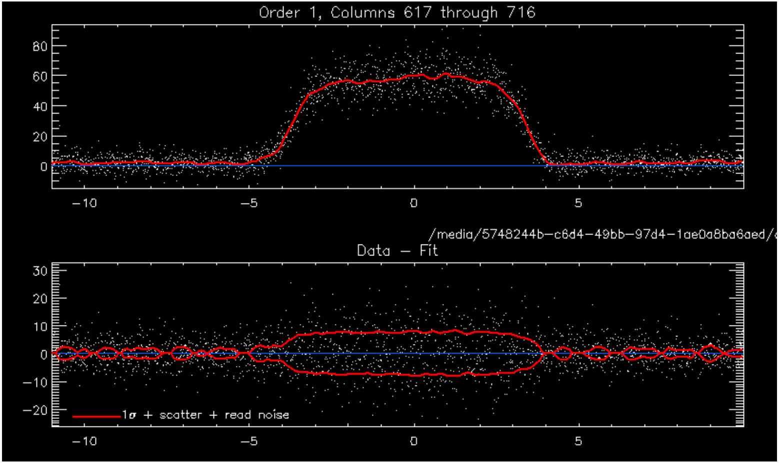
Optimal Extraction



Optimal Extraction

- example profile modeling with REDUCE (Piskunov & Valenti, 2002) (penalised splines, chunk wise modelling)

  low S/N (HET HRS spectrum)



Optimal Extraction

- example profile modeling with REDUCE (Piskunov & Valenti, 2002)

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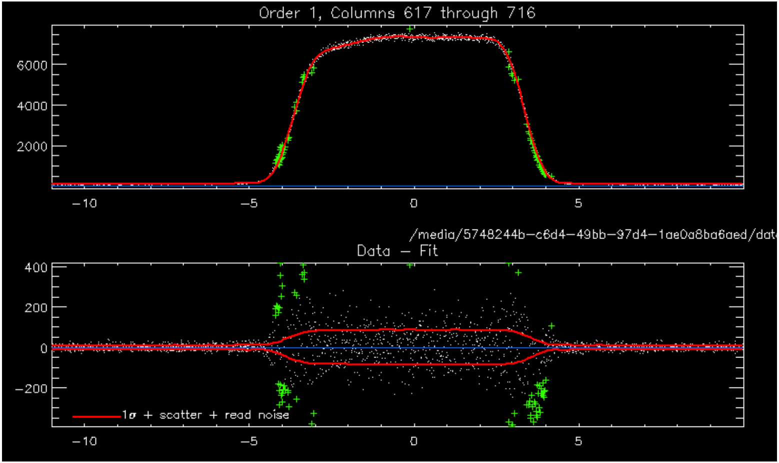
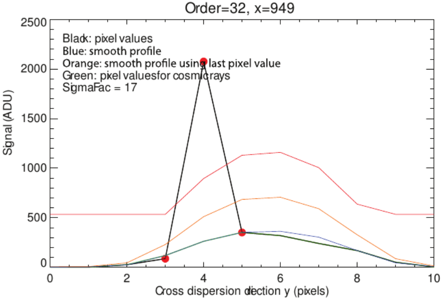
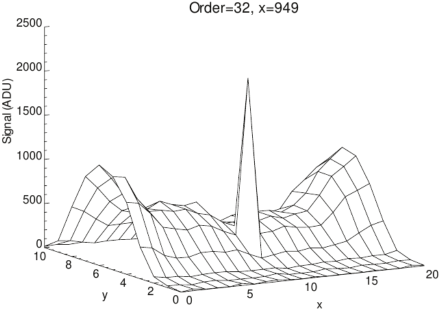


Extraction – cosmics

- cosmic ray hits
  - random events
  - number depends on exposure time
- outlier from the spatial profile
- kappa-sigma clipping to remove outlier
- requires noise model quantify the significance
- iterate profile modelling and extraction

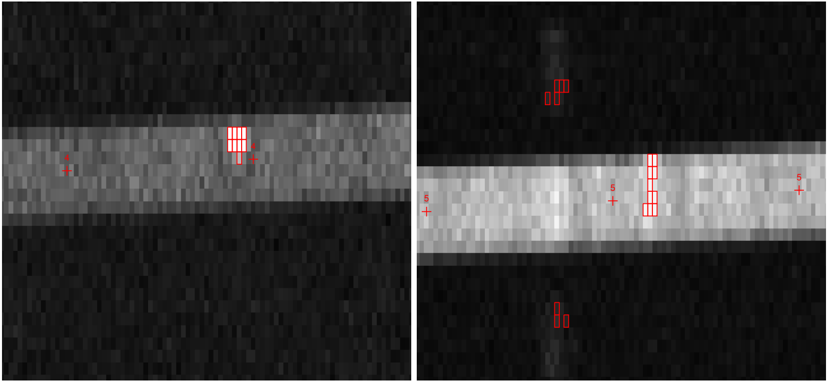




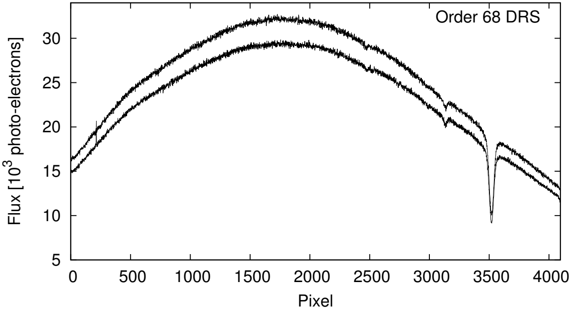
Buchhave (2010), TRES spectrograph

Extraction – Cosmics

- cosmics in the raw images (HET HRS spectrograph)



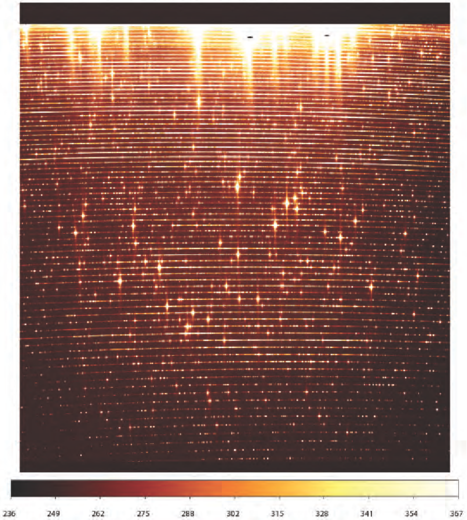
Extraction – extracted spectrum



(HARPS, B star)

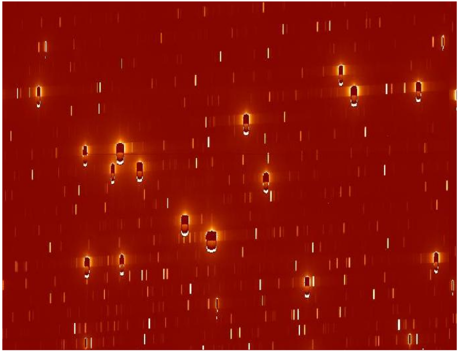
Wavelength calibration

- ThAr exposures
- emission line spectrum
- problem: saturated lines and blooming



Buchhave (2010), TRES spectrograph

Wavelength calibration

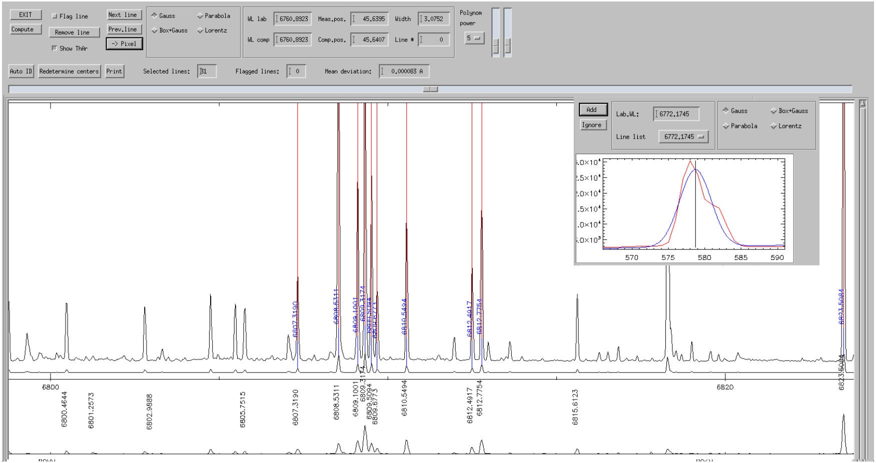


HET HRS spectrograph

- extract ThAr spectra like the science images (and deblaze)

Wavelength calibration

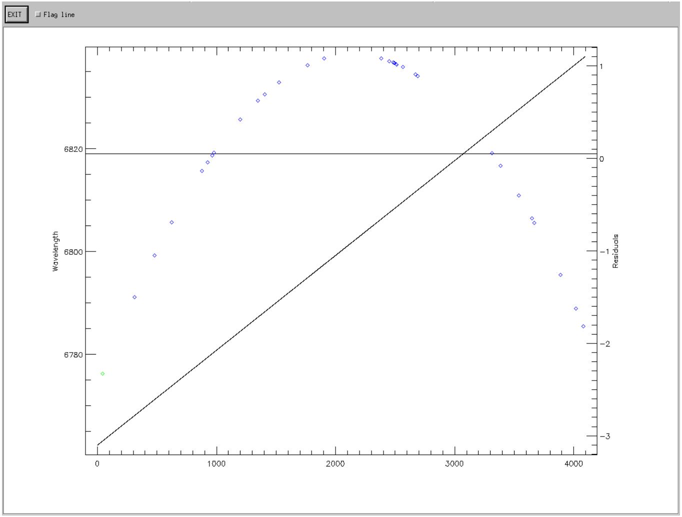
- line identification on extracted spectra
- requires a line list atlas



(IDL REDUCE)

Wavelength calibration

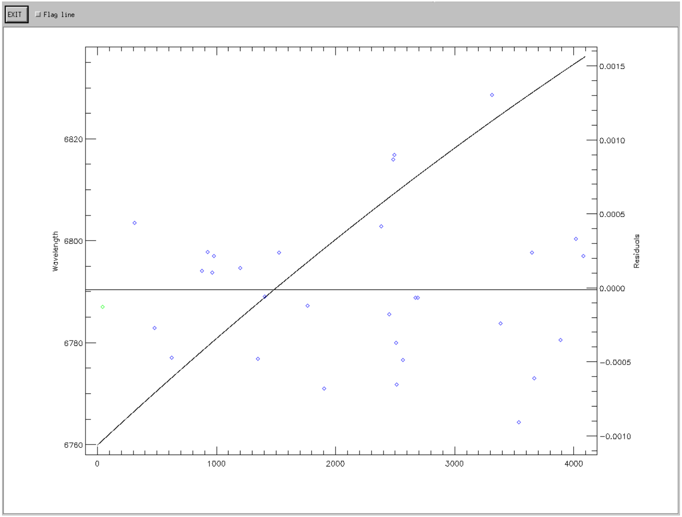
- wavelength solution: $\lambda_x = f(x)$



linear polynom (deg=1) (IDL REDUCE)

Wavelength calibration

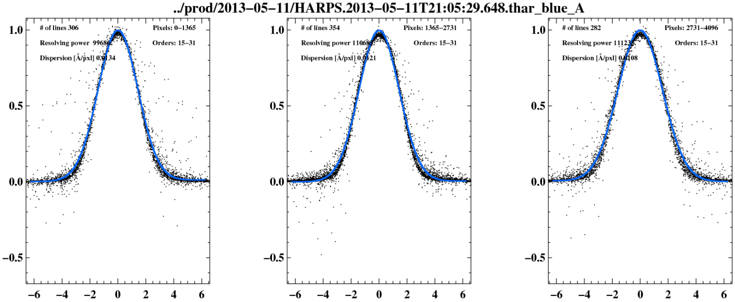
- wavelength solution: $\lambda_x = f(x)$



cubic polynom (deg=3) (IDL REDUCE)

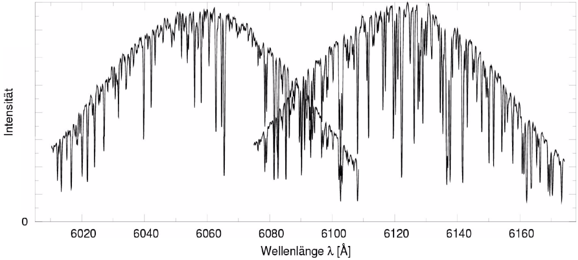
Wavelength calibration

- not all lines are used
  - unidentified lines
  - blended lines
  - Argon lines (for high precision RV, more age and pressure sensitive than Thorium)
- check line spread function (LSF)



Order merging

- extracted, wavelength calibrated spectrum

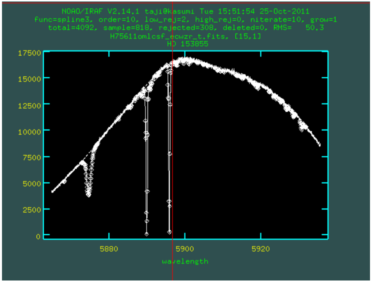


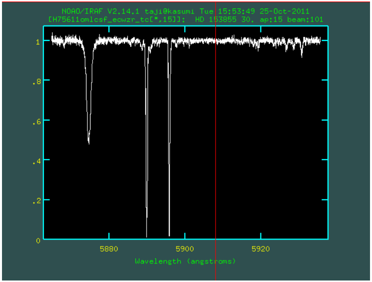
TLS spectrum (Tautenburg)

- order merging requires:
  - deblazing
  - rebinning to a common wavelength scale (sampling per resolution element is different)
  - error propagation and weighted coadding

Spectrum normalisation

- empirical normalisation (without standard star)



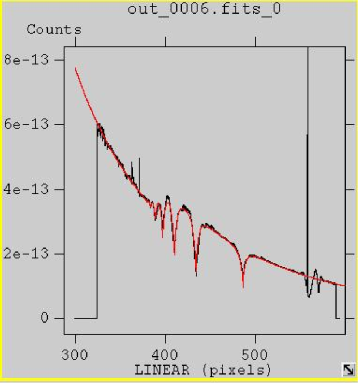


http://www.naoj.org/Observing/Instruments/HDS/hdsql-e.html

(IRAF, Subaru HDS)

Flux calibration

- derive instrument response with a spectrophotometric standard star
- extract standard star and compare with model spectrum
- $$\epsilon(\lambda) = \frac{I^{XSH}_{STD}(\lambda) \cdot 10^{0.4 \cdot Atm\_ext(\lambda) \cdot (airp - airm)} \cdot gain \cdot E_{phot}(\lambda)}{T_{exp} \cdot A_{tel} \cdot I^{ref}_{STD}(\lambda)} \cdot factor$$
    - extinction table
    - airmass
    - exposure time
- apply instrument response to object spectra

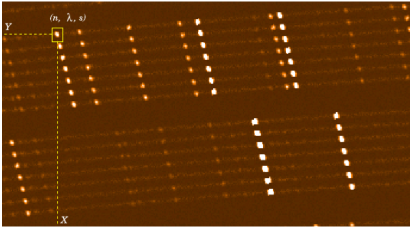


Modigliani (et al. 2012), X-Shooter

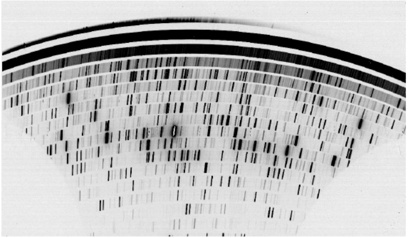
More complications

- truncated/gracing orders

- line tilt



wave map (Goldoni et al., 2006)

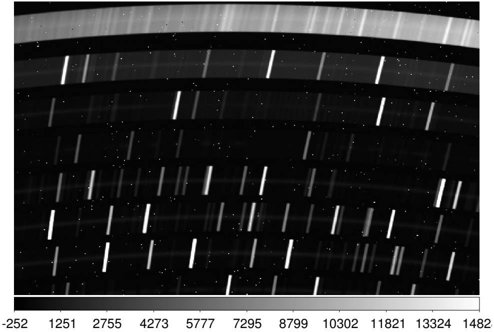


spectral format X-Shooter (NIR)

(Modigliani, et al. 2012)

More complications

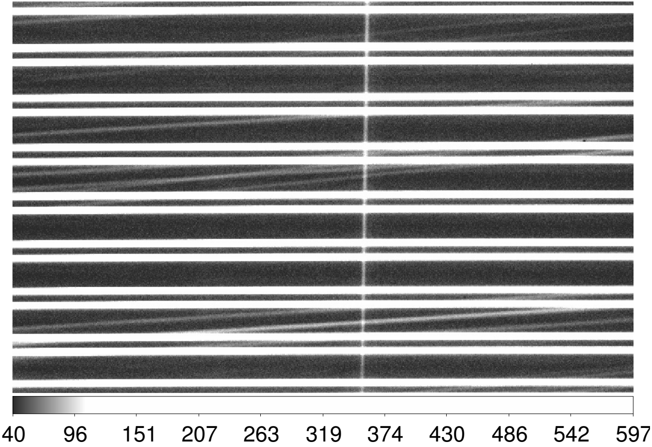
- sky emission lines



X-Shooter NIR (GJ 894.3, white dwarf, $V = 11.50\,\text{mag}$)

More complications

- ghosts (parasitic orders)



(HARPS, flat)

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