BASICS OF QUANTITATIVE SPECTROSCOPY

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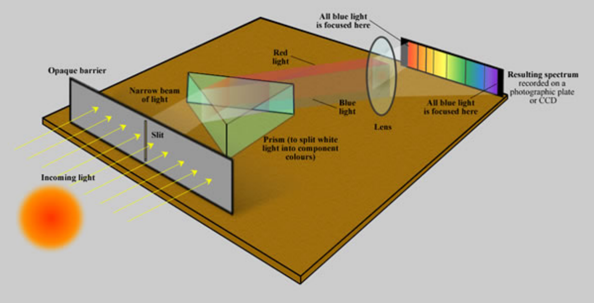
Ondřejov

Stellar spectroscopy

What it is?

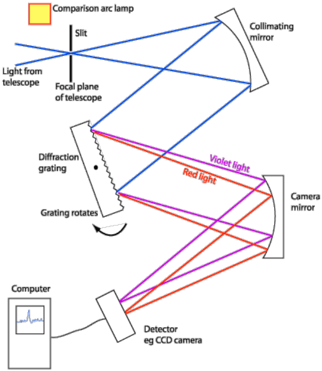
- Spectroscopy is the study of the interaction between matter and electromagnetic radiation
- The technique of splitting light (i.e., electromagnetic radiation) into its constituent wavelengths i.e., a spectrum



Credit: COSMOS - The SAO Encyclopedia of Astronomy

Stellar spectroscopy

Spectrograph

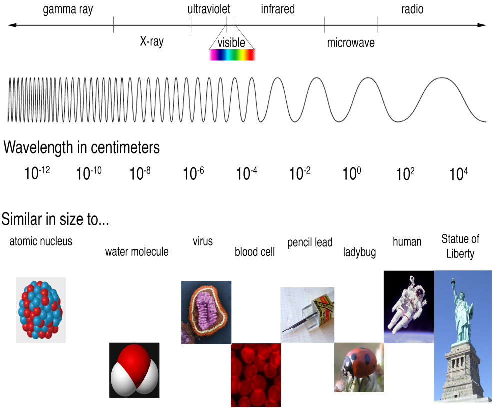


A Schematic Diagram of a Slit Spectrograph

Credit: James B. Kaler, in "Stars and their Spectra," Cambridge University Press, 1989

Stellar spectroscopy

Electromagnetic radiation



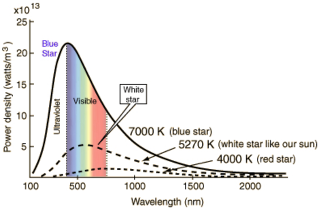
Credit: NASA's Imagine

Stellar spectroscopy

Electromagnetic radiation

Wien's displacement law

For massive, hot stars the peak radiation is in UV spectral region



$$\lambda_{max}\, T = b$$

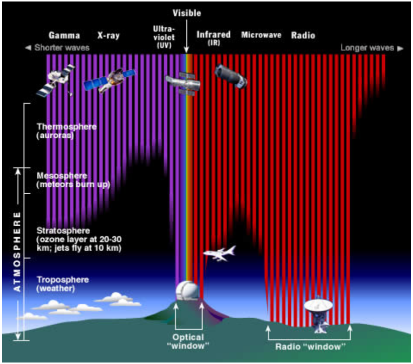
$$b = 0.29\ \mathrm{cm\,K};\quad T = 30\,000\ \mathrm{K} \Rightarrow \lambda_{max} = 960\ \text{Å}$$

Stellar spectroscopy

Electromagnetic radiation

Wavel
10
Similar
atomic

Earth Atmosphere

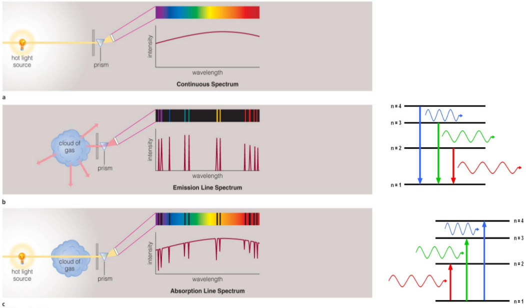


Credit: NASA's Imagine

Stellar spectroscopy

Type of the spectra

- Continuous Spectrum
- Absorption Line Spectrum
- Emission line Spectrum



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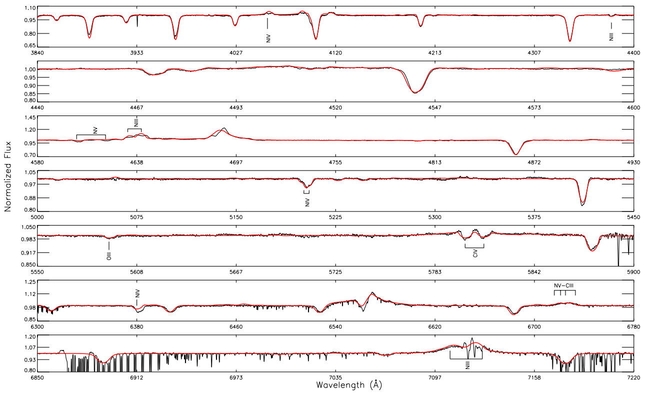
Stellar spectroscopy

Optical spectra

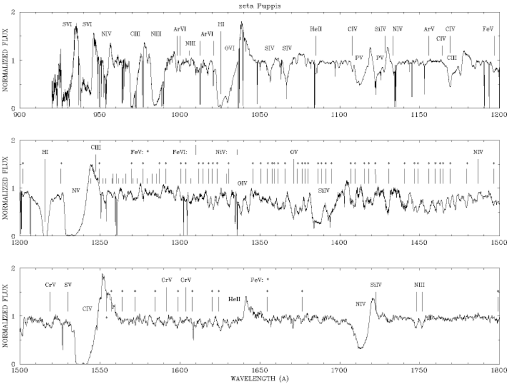
- ζ Pup observed with FEROS (Bouret et al., 2012)



Stellar spectroscopy

UV spectra

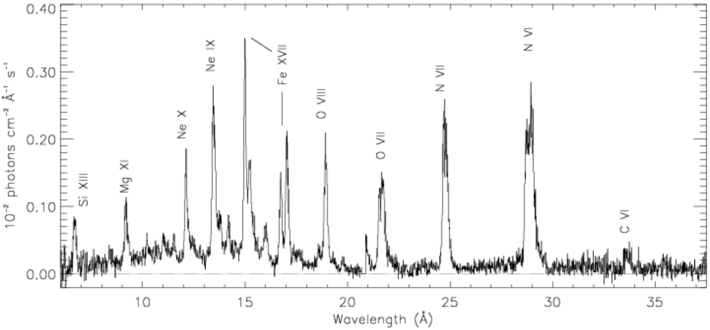
- Merged spectrum of Copernicus and IUE UV high-resolution observations of the supergiant ζ Puppis (Pauldrach et al., 1994)



Stellar spectroscopy

X-ray spectra

- ζ Pup observed with XMM-Newton (Kahn et al., 2001)



Stellar spectroscopy

SED of O-type stars

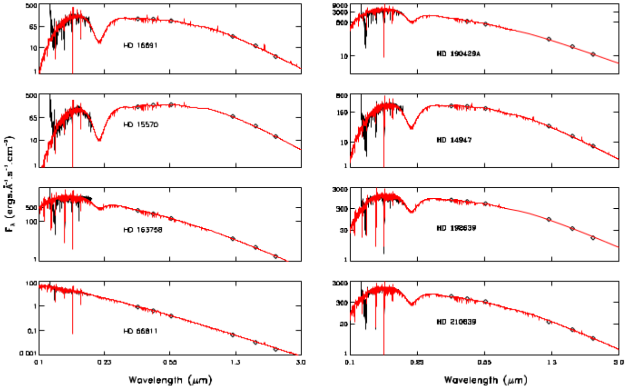
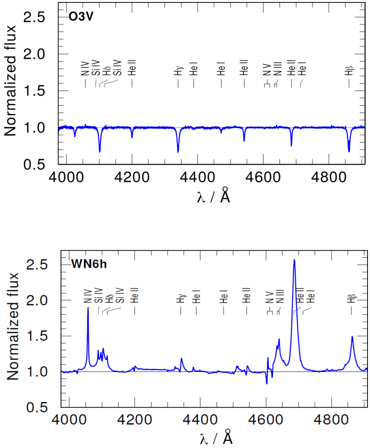


Fig. 1. Synthetic SEDs (in red) compared to flux calibrated + UBVJHK photometry for the target stars (in black). The distance, $E(B-V)$ and luminosity were iterated to reach agreement between models and observations (see Sect. 4.1). For plotting purpose, the fluxes were scaled by a factor 10^{14} for all stars but HD 66811 and HD 210839, where factors 10^9 and 10^{13} were used, respectively.

Credit: Bouret et al., 2012

Stellar spectroscopy

Spectra of O- and W-R-type stars



Credit: A. Sander

Stellar spectroscopy

What Do Spectra Tell Us?

- Identify the type of the object
- Chemical composition
- Temperature
- Density
- Velocity (Radial and Rotational)
- Properties of the star and wind
- Strength of Magnetic field
- Physical changes in the star
- Material around stars
- Accretion disk
- To study the interstellar medium

Stellar spectroscopy

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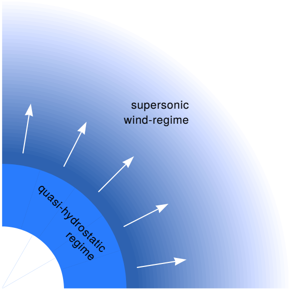
- All the information we gather about stars is derived from analysis of their radiation (spectra)
- Spectroscopy is a tool for unlocking the secrets of star light

Stellar atmosphere

Why to study stellar atmospheres?

- The stellar atmosphere is all we really see from the star
- Its spectrum is (usually) the only information we get
  $\Rightarrow$ Understand the spectrum to understand the star
- Only a proper modeling of the atmosphere can reproduce the emergent spectrum



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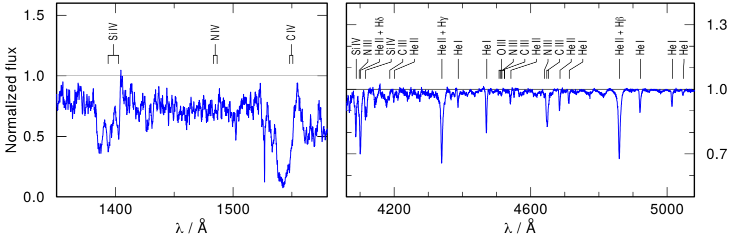

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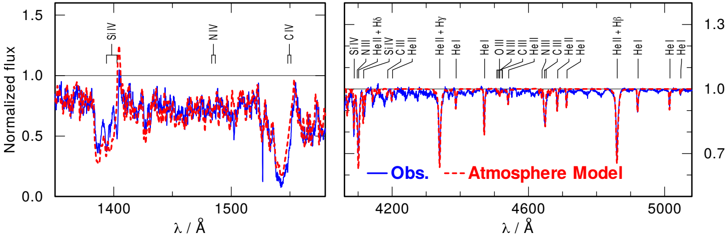

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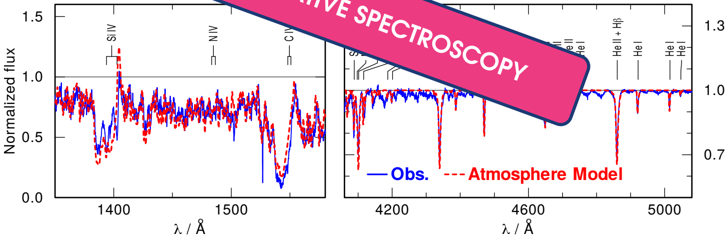

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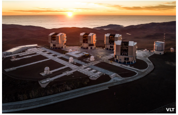
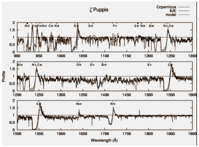
QUANTITATIVE SPECTROSCOPY

What is QS?

- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an **inversion problem** $d_{obs} = F(p)$
- The process of calculating from a set of observations the causal factors that produced them





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The ingredients

- Observed data (spectra)
- Theoretical spectra (model atmosphere/line formation codes)
- Comparison metrics

QUANTITATIVE SPECTROSCOPY

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What should we worry about?

- **Information encoded in the observed data**
  (both quantity and quality, i.e., spectral range coverage, SNR, R, ...)
- **Physics incorporated in the models**
  (i.e., assumptions/simplifications)
- **Atomic data**
- **Comparison metrics (grid of models)**
- **Uncertainties/Errors**

Spectroscopic analysis

Steps to perform

1. **Acquisition of the observed spectrum.**
2. Pre-processing of the spectrum, including a first qualitative visual assessment. To correct the observed spectrum for nebular contamination, cosmic rays, the radial velocity correction and to do continuum normalization.
3. Determination of the line-broadening parameters. This is the basic step to have access to projected rotational velocities.
4. Identification of the stellar atmosphere code and atomic models best suited for the analysis of the star under study.
5. Creation of a grid of stellar atmosphere models. Define the free parameters (parameter space), the range of values for the various free parameters, fix some parameters.
6. Identification of the analysis strategy best suited to extract information from the observed spectrum of the star under study.
7. Determination of the main set of spectroscopic parameters accessible through the analysis of the observed piece of spectrum (*stellar parameters determination).*
8. Determination of surface abundances of interest (*chemical abundance analysis).*

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Stellar Atmospheres Models

Stellar parameters

- Effective temperature $T_{\rm eff}$ [K]
- Surface gravity $\log g$
- Helium abundance $Y = H/He$
- Stellar luminosity L_* $[L_\odot]$
- Stellar radii R_* $[R_\odot]$
- Micro-turbulent Velocity
- Chemical Abundances

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Wind parameters

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- Mass-loss rate $\dot{M}$ $[M_\odot/yr]$
- Beta parameter β

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By fitting the SED

- Distance (global scaling)
- Interstellar Extinction (Reddening) "color exces" $E_{(B-V)}$
- Magnitude of star has to be known

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Photospheric stell. atm. models

- ATLAS/DETAIL SURFACE (Kurucz 1970, 1994, Butler & Giddings, 1985)
- TLUSTY/SYNSPEC (Hubeny, 1988)

Wind parameters

- Terminal velocity v_∞ [km
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Photospheric + Wind models

- CMFGEN (Hillier & Miller, 1998)
- FASTWIND (Puls et al., 2005)
- PoWR (Hamann & Gräfener, 2004)
- WM-basic (Pauldrach el al., 2001)

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What has to be included?

- **Extreme non-LTE situation**
- Model atoms for H, He, C, N, Fe, etc. (atomic data)
- Line blocking/blanketi
- Modeling two regimes (core) + Supersonic wi
- Inhomogeneities
- Other ...

NLTE

- Intense radiation field + Low densities in lines and continuum forming regions
  $\Rightarrow$ Collisions are less important in hot star atmospheres

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Atomic data

- Collisional cross sections
  - OPAL PROJECT (Iglesias & Rogers 1996)
  - OPACITY PROJECT (Seaton et al. 1992)
  - IRON PROJECT (Hummer et al. 1993, Witthoeft & Badnell 2008)
- Super-level approach - simplified treatment of iron-group atoms (Anderson 1985, 1989)

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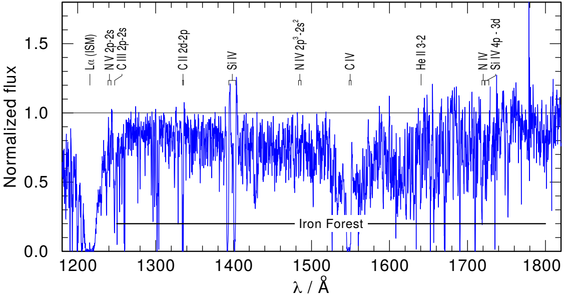
Blanketing and blocking



Credit: A. Sander

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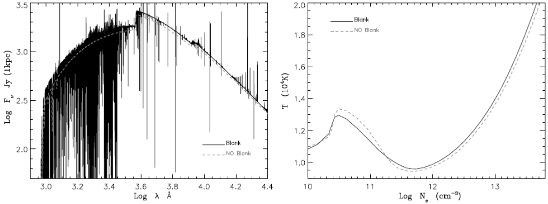

Figure 2: Effects of line blanketing (solid: blanketed model, dashed: model without blanketing) on the flux distribution ($\log F_\nu$ (Jansky) vs. $\log\lambda$ (Å), left panel) and temperature structure ($T(10^4$ K) vs. $\log n_e$, right panel) in the atmosphere of a late B-hypergiant. Blanketing blocks flux in the UV, redistributes it towards longer wavelengths and causes back-warming. From Puls et al. (2008).

Credit: J. Puls

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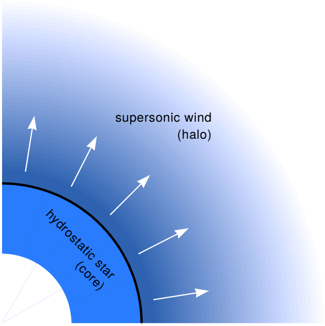
Modeling two regimes



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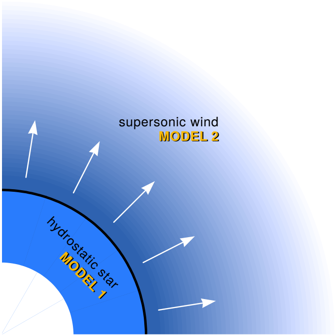
Modeling two regimes

- Traditional core-halo approach: Two separate models



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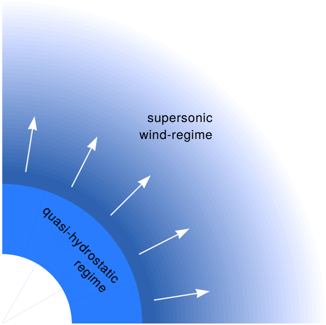
Modeling two regimes

- Modern approach, since ≈ 1990s:
  Unified model atmospheres
  (e.g. Hamann & Schmutz 1987, Gabler et al., 1989)



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Wind clumping

- Simplification: Clumping factor $D \Longrightarrow \rho_{\mathrm{cl}} = D\rho_{SW}$; void inter-clump medium; monotonic velocity field
- Microclumping approach - clumps are optically thin at all frequencies (FASTWIND; CMFGEN ; PoWR)
- 3-D description of clumping from other codes

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Other effects

- Stellar rotation
- Magnetic field
- Pulsation
- ...

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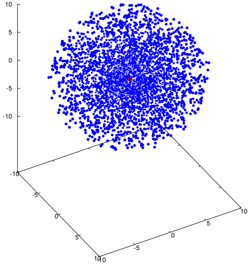
- Microclumping approach - clumps are optically thin at all frequencies (FASTWIND; CMFGEN ; PoWR)
- 3-D description of clumping from other codes

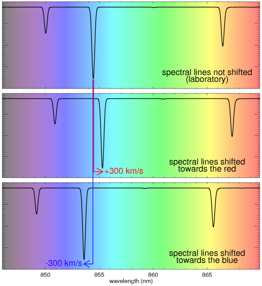


Šurlan et al., 2012

Radial velocity correction

Radial velocity

- The observed spectrum must be corrected by Doppler shift to ensure that all diagnostic lines are located in the laboratory position.
- Standard techniques
  - Identification of the core of one or several diagnostic lines.
  - Cross-correlation with a template.



Line-broadening parameters

Rotational velocity

- **Inferring the projected component of the equatorial rotational velocity (v**sin *i*) **by disentangling the effect that rotation produces on the line-profile.**
- **A well isolated photospheric metal line than a hydrogen or helium line are better to use.**
- **Methods**
  - **The combined use of the Fourier transform and a goodness-of-fit methods**
  - **Synthetic line resulting from a stellar atmosphere code – is convolved with a rotational and a macroturbulent profile**

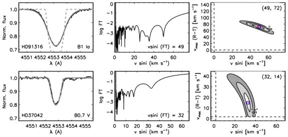


Fig. 5 Combined FT+GOF line-broadening analysis of the Si III λ4552 Å line in the early-B dwarf HD 37042 (bottom) and the early-B supergiant HD 91316 (top). [Left panels] The best fitting synthetic profile (solid gray) and the profile corresponding to $v \sin i$(FT) and $v_{\rm mac} = 0$ (dashed gray) are over plotted to the observed profile (solid black). [Middle panels] Fourier transform of the observed profile. [Right panels] χ^2-2D-map resulting from the GOF analysis.

Credit: Simón-Díaz, 2020

Line-broadening parameters

Micro-turbulence velocity

- Form of turbulence that varies over small distance scales
- Convection - the mechanism believed to be responsible for the observed turbulent velocity field
- Varies with the effective temperature and the surface gravity
- Velocity fields with a scale that is shorter than the mean free path of the photons in the atmosphere
- Microturbulenceis usually treated in model atmospheres as a free parameter (ξ_t) that allows to re-establish agreement among abundances derived from different lines

$$\xi_t(r) = \xi_t^{min} + (\xi_t^{max} - \xi_t^{min}) \cdot \frac{v(r)}{v_\infty}$$

Line-broadening parameters

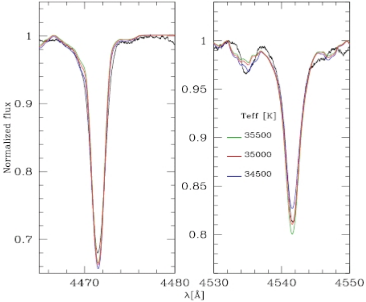
Macro-turbulence

- Howarth et al., 1997 - OB stars from IUE spectroscopy: important line broadening mechanism in addition to rotation
- Refers to velocity fields with a scale longer than the mean free path of the photons
- Macroturbulence of the order of several tens of km/s
- Aerts & De Cat, 2003 - take into account pulsational velocity fields; pulsational broadening in the line-prediction code
- Pulsational velocity broadening due to the collective effect of numerous low-amplitude gravity mode oscillations offers a natural and appropriate physical explanation for the occurrence of macroturbulence in hot massive stars

Determination of the effective temperature

Optical diagnostics

- T_{eff} is derived using the ionization balance method (e.g. Herrero et al. 1992, Puls et al. 1996, Martins et al. 2002)
- He I 4471 and He II 4542 lines - the most reliable indicators for O and WR stars



Martins, 2011

Determination of the surface gravity and luminosity

Optical diagnostics

- log g is derived using the wings of the Balmer lines.
- $H\beta$, $H\gamma$ and $H\delta$ lines are the main indicators.
- Spectral energy distribution (SED) fitting is becoming the standard way of deriving luminosities.

THANK YOU FOR YOUR ATTENTION!

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