Atomic data for iron-group elements of astrophysical interest.

NIST:

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Imperial College, London:

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Program is a collaboration between NIST and Imperial College, London, with ICL carrying out measurements of UV FT spectra and NIST the measurements of vis/IR FT spectra and VUV/UV grating spectra.

Why iron-group elements?

Iron-group elements are found in almost all astrophysical objects, including:

- Stars.
- Nebulae around stars.
- Inter-stellar and inter-galactic medium.
- Galaxies
- Quasi-stellar objects and QSO absorption-line systems

Accurate atomic data are needed to interpret the spectra from all of these objects.

What atomic data are needed?

Data needs include:

- **Line identifications:** chemical abundances, blended lines.
- **Wavelengths:** for radial velocities, line identification, α.
- **Oscillator strengths:** chemical abundances, spectrum synthesis.
- **Hyperfine & isotope structure:** abundances, spectrum synthesis

Iron-group elements in χ Lupi: accurate line identifications are essential!

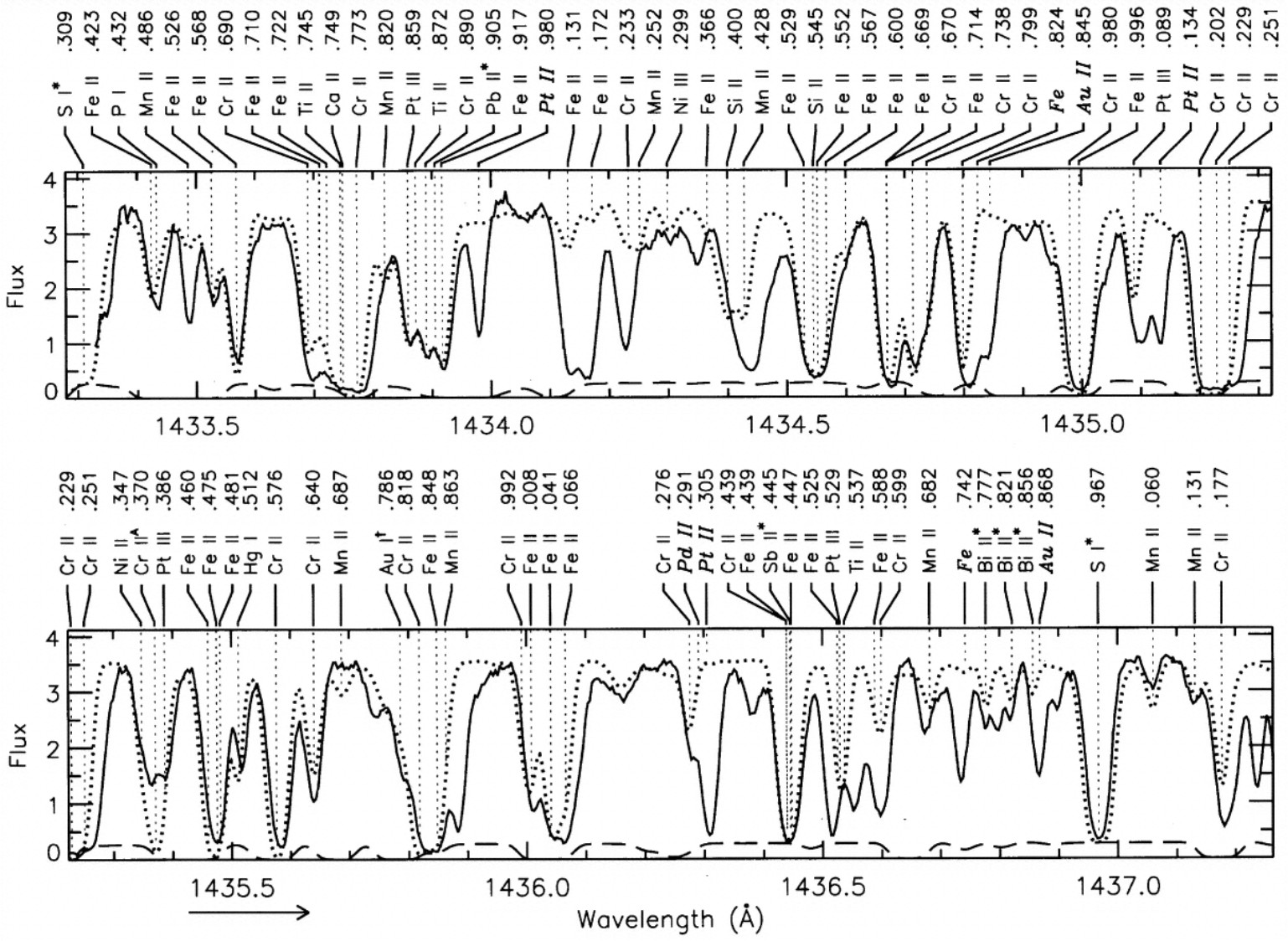
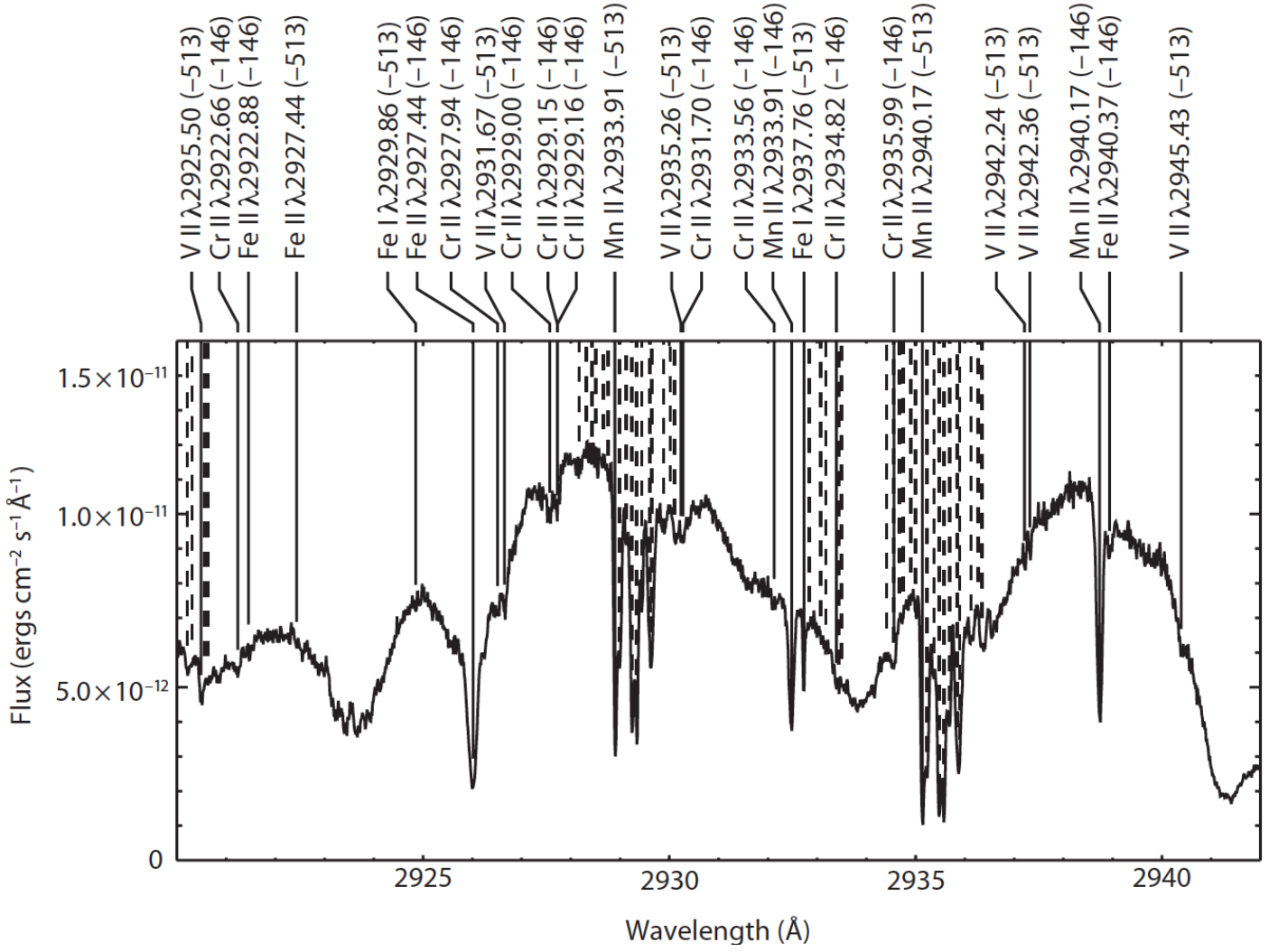


Figure from Brandt et al. Astron. J. 117, 1505-1548 (1999)

Iron-group elements in η Carinae



"The measurements of velocities and column densities of the ejecta absorption lines are highly dependent on the availability and accuracy of atomic data" (Nielsen & Gull, Phs. Scr. T134, 2009)

Spectroscopic surveys: Gaia-ESO Public Spectroscopic Survey (visible)

Gaia-ESO survey complements ESA's GAIA mission.

GAIA will perform astrometry & photometry on stars > mag 20.

Gaia-ESO survey is measuring visible-region spectra of 10^5 stars using FLAMES (UVES & GIRAFFE) spectrographs on UT2 of ESO's VLT.

Oscillator strengths are needed in Fe I for lines with poor ratings in NIST Atomic Spectra Database (D or E).

FLAMES/GIRAFFE: 130 targets, R= 25000.

FLAMES/UVES: 8 targets, R=47000

Wavelengths: 300 nm – 1100 nm.

APOGEE: Apache Point Observatory Galactic Evolution Experiment

Part of the SDSS III & aims to measure chemical abundances for 100,000 stars.

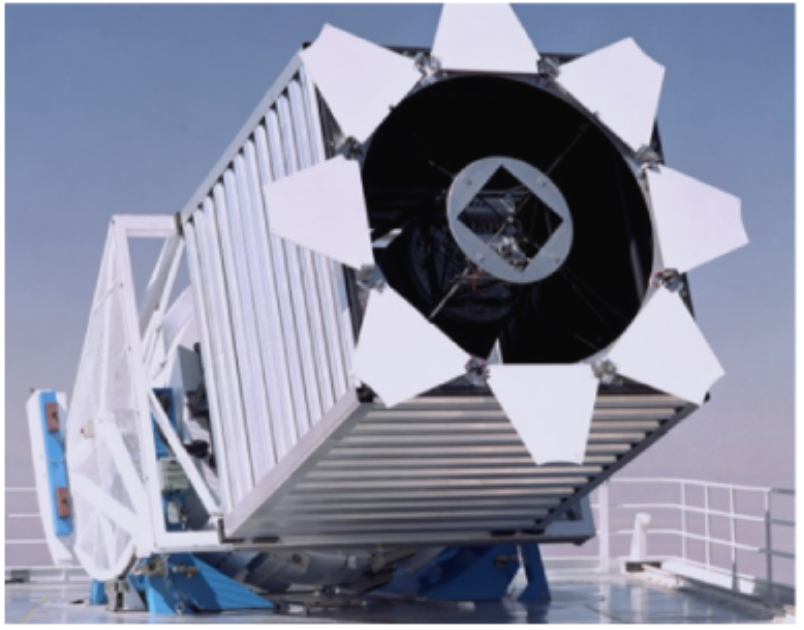
Cryogenic Spectrograph with R ~24,000

Wavelengths: 1.51 – 1.68 μm (H-band)

Abundances to 0.1 dex (25%) for 10^5 stars

Problem:

Few IR oscillator strengths:



Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
–	45	7	–	26	51	–	4	–	1

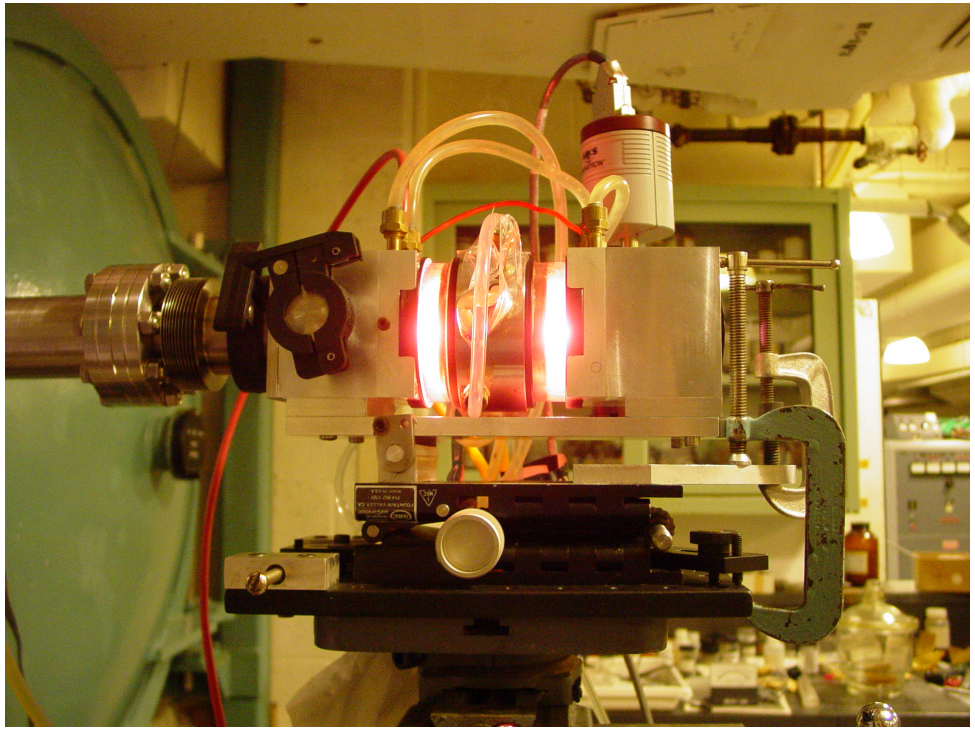
Joint project between ICL, NIST, & Univ. Wisconsin, Madison to measure Fe I 4d-4f, 5s-5p transitions.

Recent work on iron-group spectra (energy levels and wavelengths)

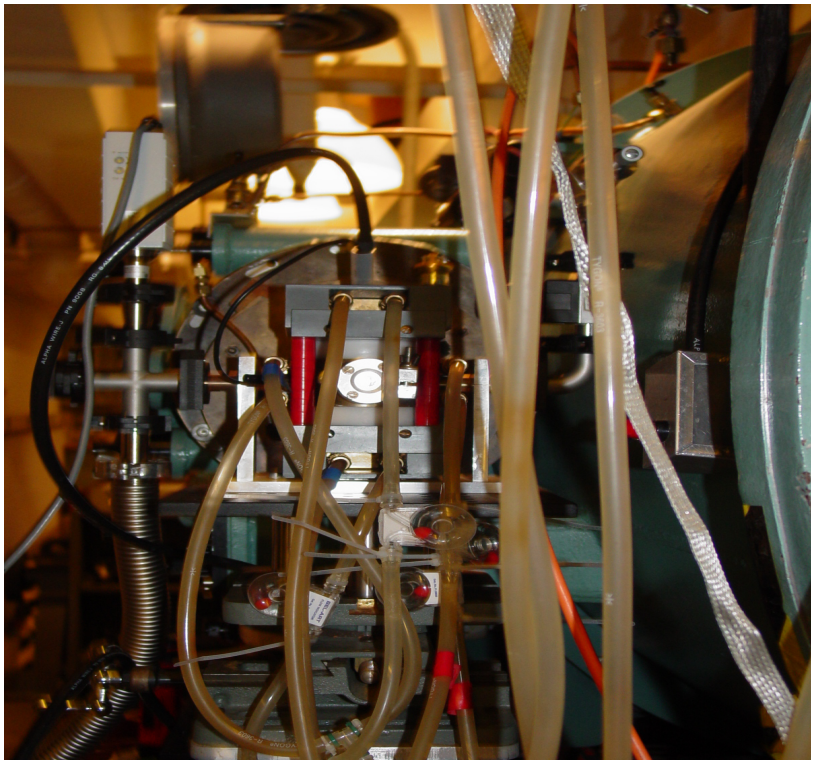
Element	1st spectrum	2nd spectrum >150 nm	2nd spectrum <150 nm
Sc			
Ti	Forsberg 1991	unpub. in ASD	
V	Thorne et al. 2011	In progress at ICL	
Cr	Wallace et al. 2009 (>250 nm) / in progress at ICL	Sansonetti et al. (UV in press, vis/IR in progress.	
Mn	In progress at ICL/NIST	Begun at ICL	
Fe	Nave et al. 1994		Nave et al. (submitted)
Co	Pickering et al (1996) (incl. HFS for 297 levels)	Pickering et al. (1998)	
Ni	Litzén et al (1993)	Begun at ICL	

Older grating measurements are available for many spectra, but are of variable quality.
Comprehensive HFS measurements completed for Co I, but missing for many other elements.

Sources



High current hollow cathode source. Suitable for neutral and singly-ionized spectra.



Penning discharge source. Suitable for singly-ionized and doubly-ionized spectra.

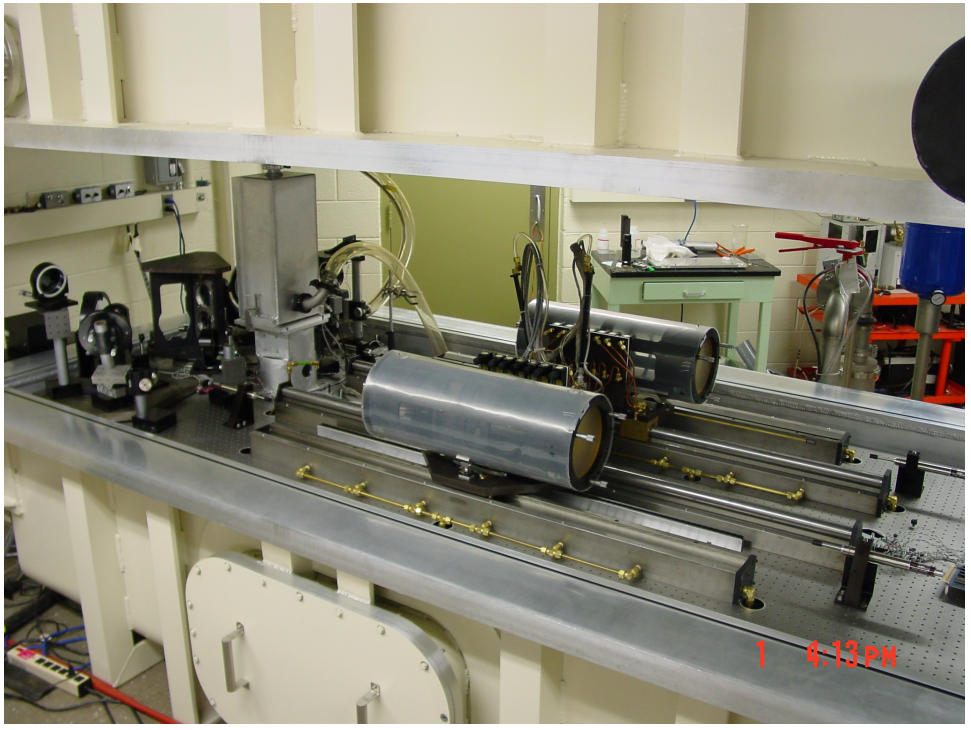
IMPERIAL COLLEGE FTS LABORATORY

- Part of the Space & Atmospheric Physics Group
- 2 FT spectrometers

Maximum path difference	20 cm
Resolving power	2,000,000 @ 200 nm
Resolution limit	0.025 cm^{-1}
Maximum free spectral range	64,000 cm^{-1}
Wavelength range covered	1.15 μm – 135 nm

- Transition wavelengths: **few parts in 10^8 uncertainty**
- FTS linelist & energy level uncertainty **0.002 cm^{-1}**

NIST 2-m vis/IR Fourier transform spectrometer

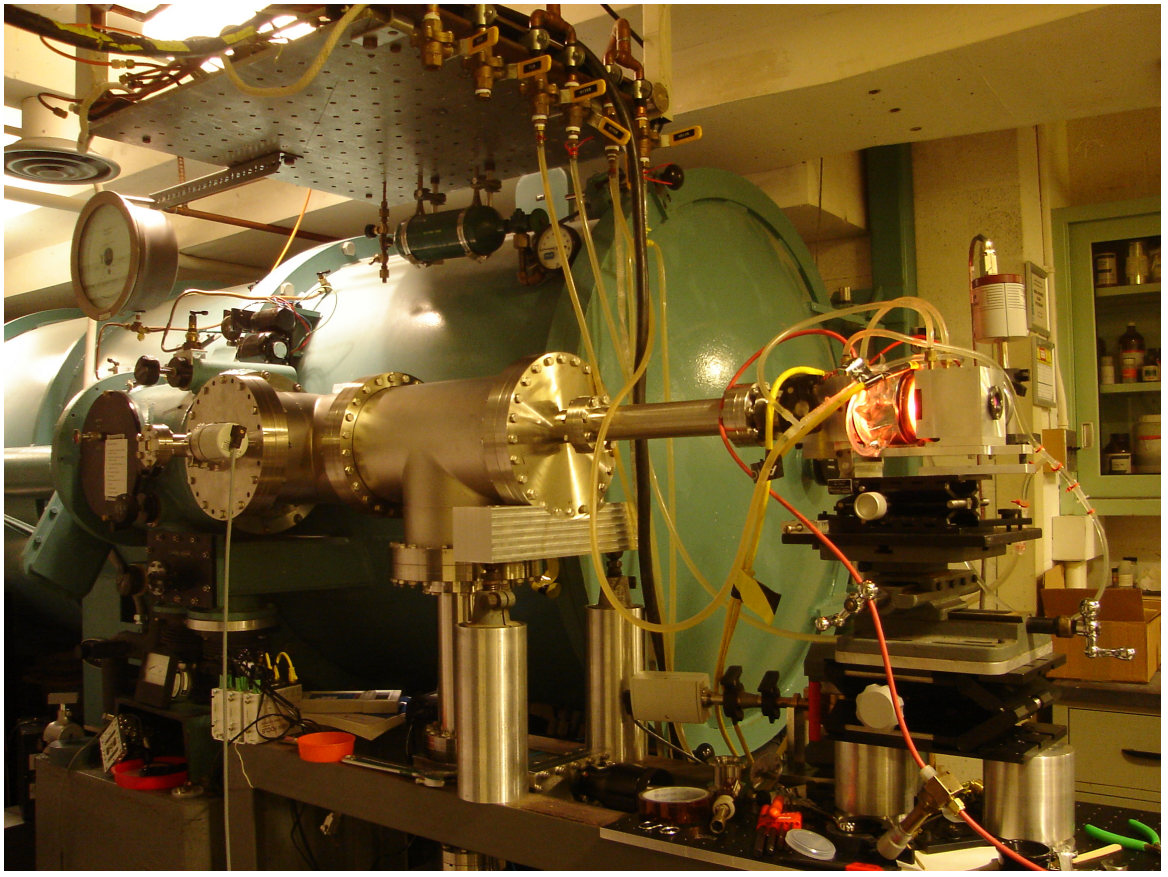


Wavelength range: 2200 Å – 5.5 μm.

Resolution: 0.0025 cm^{-1} (4 million at 1 μm).

Typical wavelength uncertainty for strong lines: <3:10^8

Grating Spectrometer



Normal incidence vacuum spectrograph.

Wavelength range: 300 Å – 5000 Å.

Resolving power: ≈150000 (1st order, on photographic plates).

Photographic plates vs image plates

Photographic plates	Phosphor image plates
Wavelengths up to 5000 Å	Wavelengths up to 2200 Å
Resolution of a few µm.	Resolution of >50 µm.
Non-linear intensity scale	Linear intensity scale
No longer manufactured	Commercially available
Single use	Reusable

Both types of plates are being used for this project. We have about 100 photographic plates in storage.

If you have photographic plates of iron-group elements we would be very interested in collaborating with you !!!

New scanner for photographic plates.

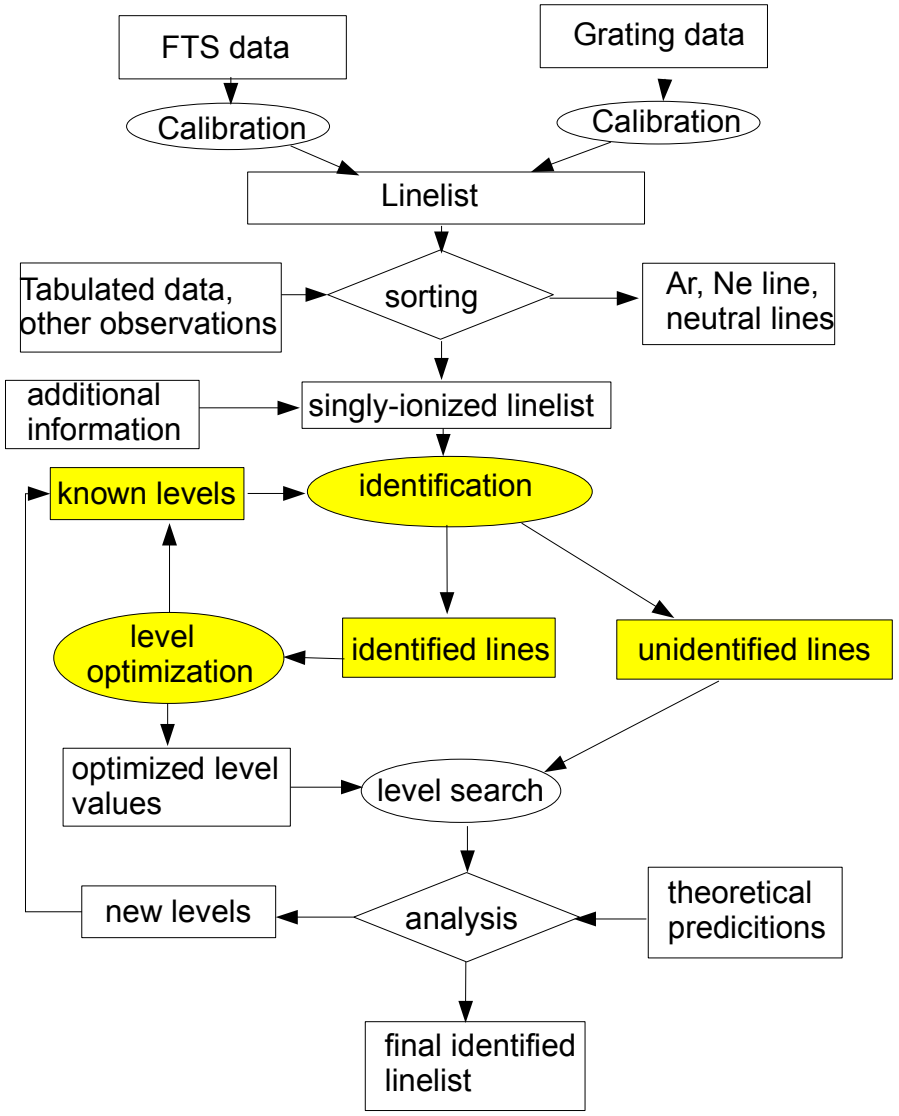
NIST currently has:

- About 2000 plates from normal incidence spectrograph.
- Similar number from Grazing incidence spectrograph.
- About 1100 Zeeman plates from MIT.
- Assorted plates from other spectrographs (few hundred?)

Many of these plates are unique and cannot be taken again.

We are investigating designs to provide rapid scanning of these plates.

Term Analysis



Fe II (NIST)

G. Nave, S. Johansson, Ap J. Suppl. Series (submitted)

See poster #4 on Wednesday

- Measurements using FTS and grating spectroscopy.
- 12 887 spectral lines classified using 1027 energy levels (13654 transitions).
- Spectral range 900 Å – 5 μm.
- Uncertainties of FT spectra from 0.0001 cm^{-1} in IR to 0.05 cm^{-1} in UV.
- Uncertainties of grating lines are 0.005 cm^{-1}.
- Ritz wavelengths for all lines – brings grating data to FTS precision.
- Spectra being put into ASD as soon as they are published.

Ultraviolet spectrum of Cr II (NIST/ESA/ESO)

C. J. Sansonetti, G. Nave, J. Reader, F. Kerber, Ap. J. Suppl. Series 202, 15 (2012).
See poster # 6 on Monday

- FTS and grating observations in region 1142 – 3954 Å in press.
- >3600 lines classified using 651 levels of Cr II.
- Uncertainties reduced by about a factor of 20.

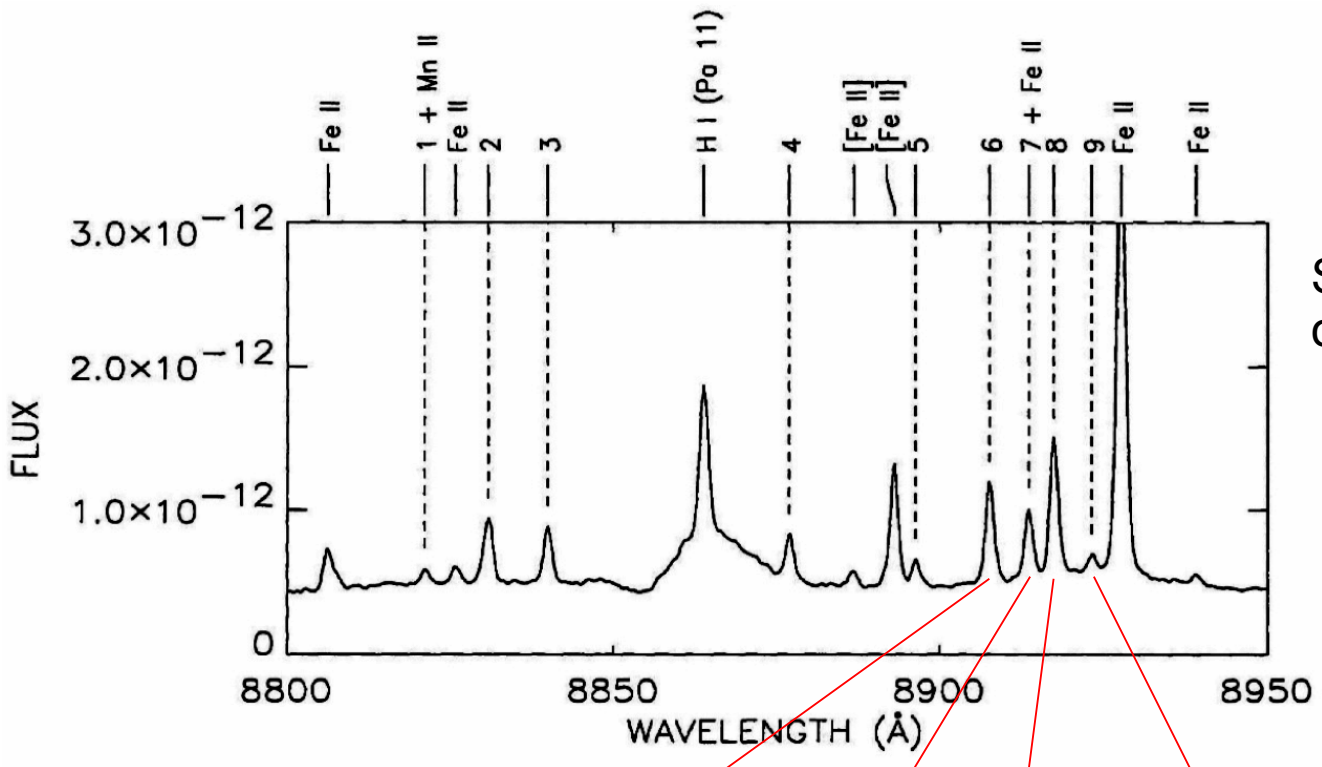
Visible/IR spectra of Cr II

New spectra recorded with NIST 2-m FTS in region 4000 Å to 5.5 μm.

Brings total of classified lines to almost 4500, covering 1130 Å – 5.5 μm.

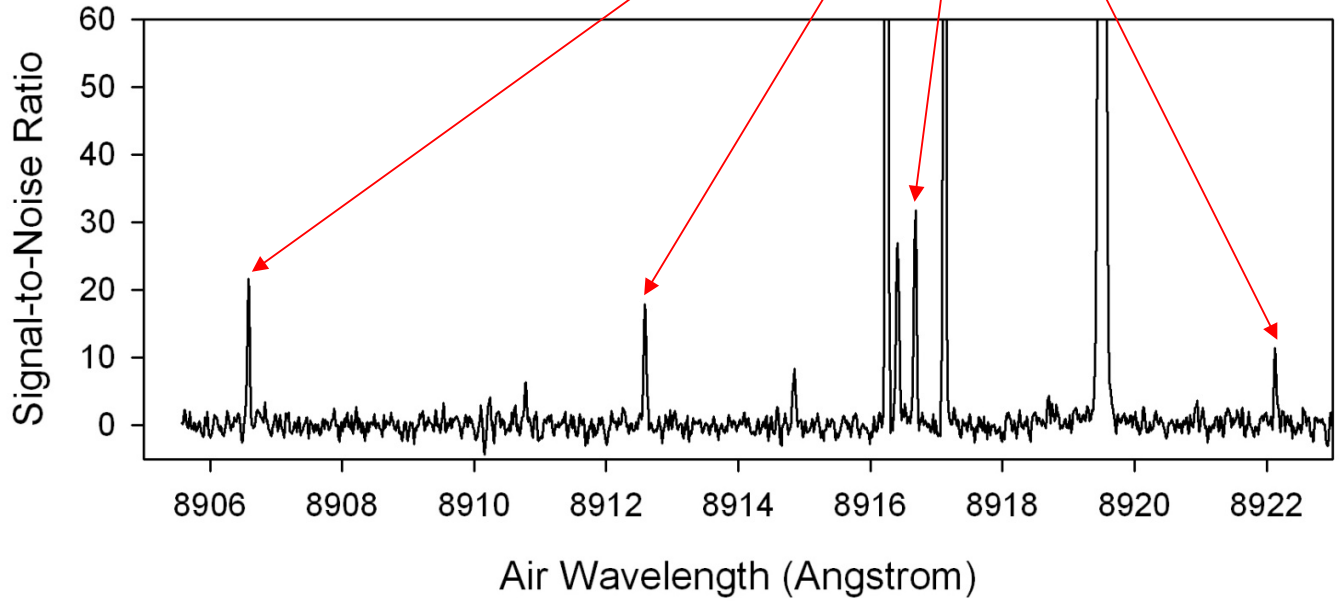
Total number of optimized levels now 728.

Fluorescence lines of Cr in η Car



STIS spectrum of one of the Weigelt blobs

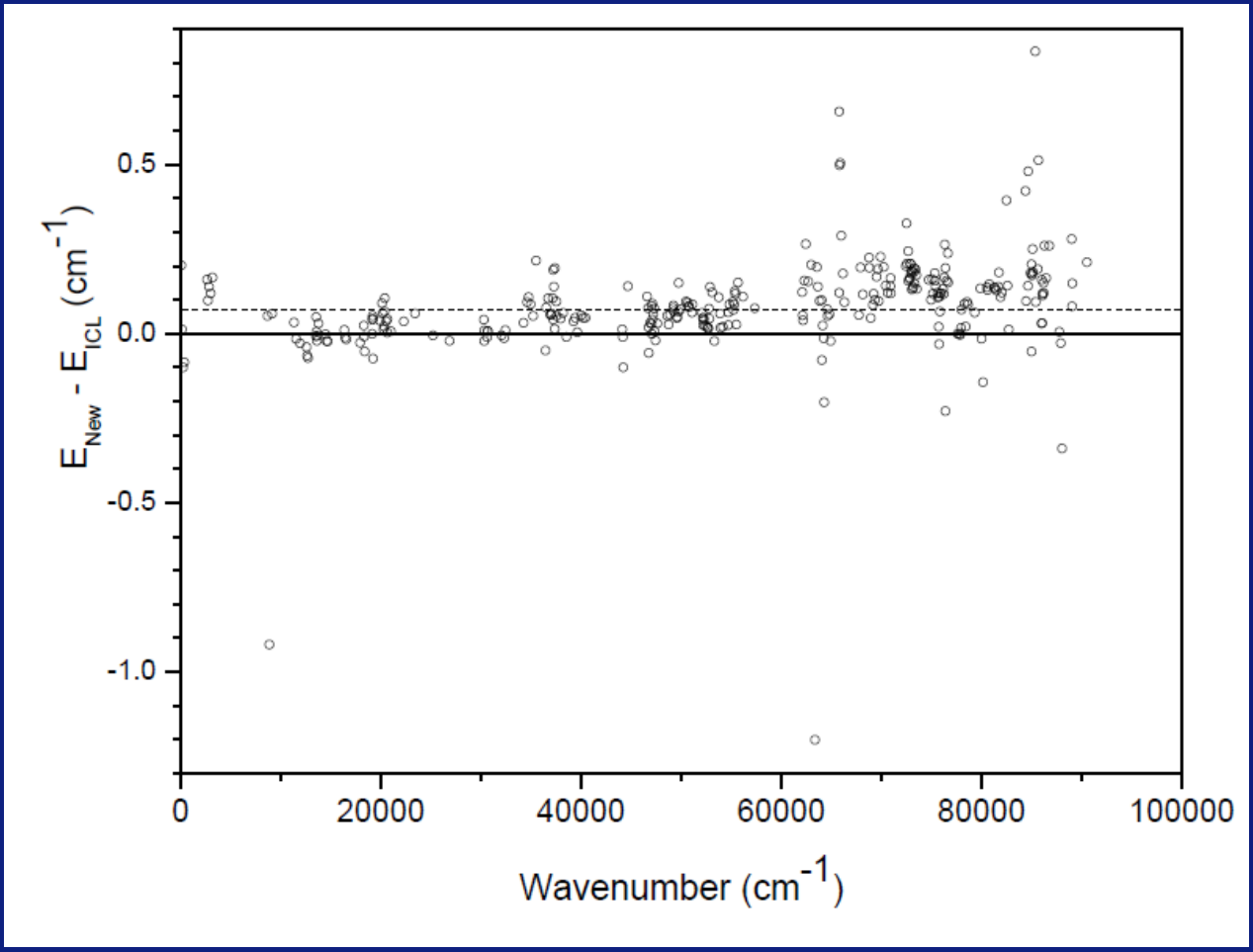
T. Zethson et al., ASP Conf. Ser. **242**, 97 (2001)



Laboratory spectrum

V II

A. P. Thorne, J. C. Pickering, J. I. Semeniuk, Ap. J. Suppl. Series (in press)



FTS spectra of V/Ne hcl covering 1490 Å – 5800 Å. 1242 lines of V II from 409 levels.

Plot shows difference between revised and previous energy levels of V II (Iglesias, Catalan et al). Uncertainty of the new level energies is typically in the range from 0.002cm^{-1} to 0.005cm^{-1}.

Mn I (NIST/IC)

R. Blackwell-Whitehead, J. Pickering, G. Nave, in preparation

- Analysis of both of these spectra was begun at Imperial College (ICL), London, using spectra from ICL and NIST.
- List of about 1300 lines of Mn I measured using FTS, classified using 275 levels. Covers region 1913 Å – 5.1 µm with uncertainties of 0.001 – 0.005 cm^{-1}.
- Poor agreement between observed wavelengths and Ritz wavelengths suggests level optimization can be improved.

Co III

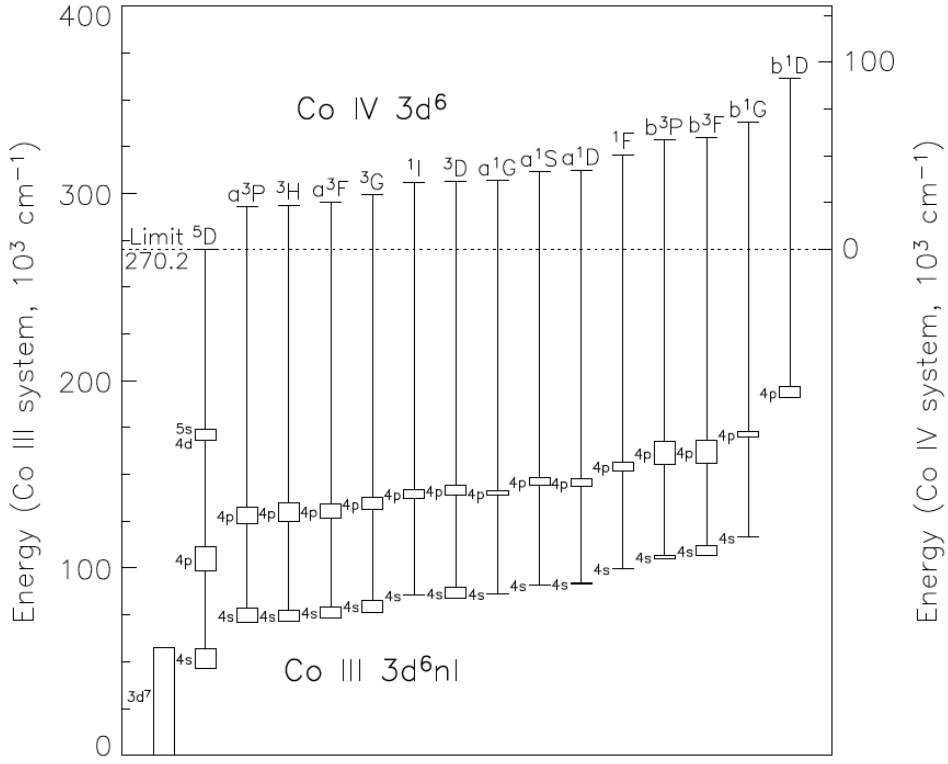
D. G. Smillie, J. C. Pickering, G. Nave, P. L. Smith (in preparation)

List of about 1100 lines of Co III measured using FTS and grating spectroscopy with phosphor image plates.

Co/Ne Penning discharge source: 1.7 A, 0.1 Pa Ne.

Covers region 610 Å to 2564 Å with uncertainties of 0.004 cm^{-1} for FTS lines.

Classified using 215 Co III levels: best improvement is going to be for the 4s-4p lines.



Are lists of classified lines enough?

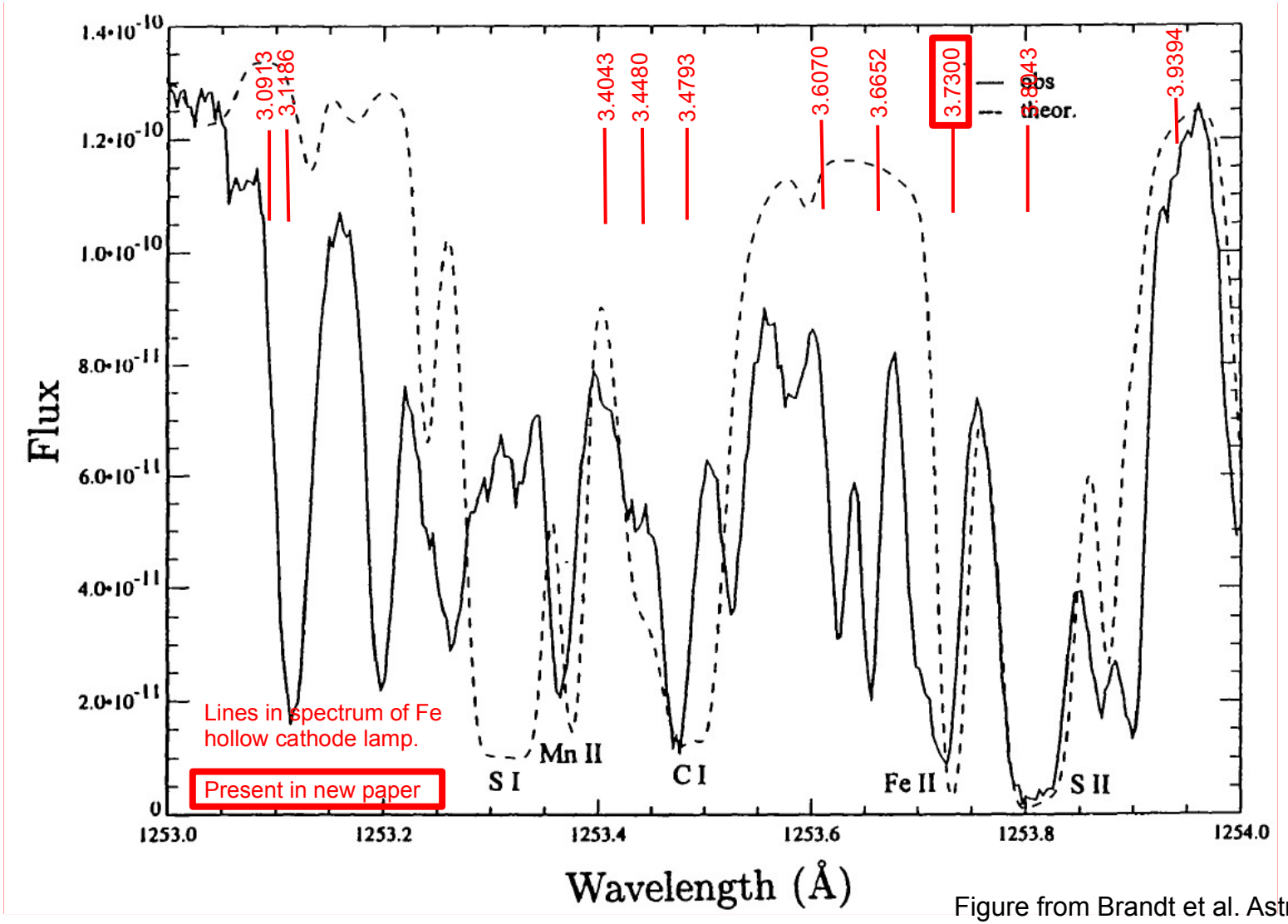


Figure from Brandt et al. Astron. J. 117, 1505-1548 (1999)

We need lists of unclassified lines too!

Acknowledgments

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We thank all the astronomers who have given us support in the past. Continued strong support by the astronomical community is absolutely vital for this work to continue!