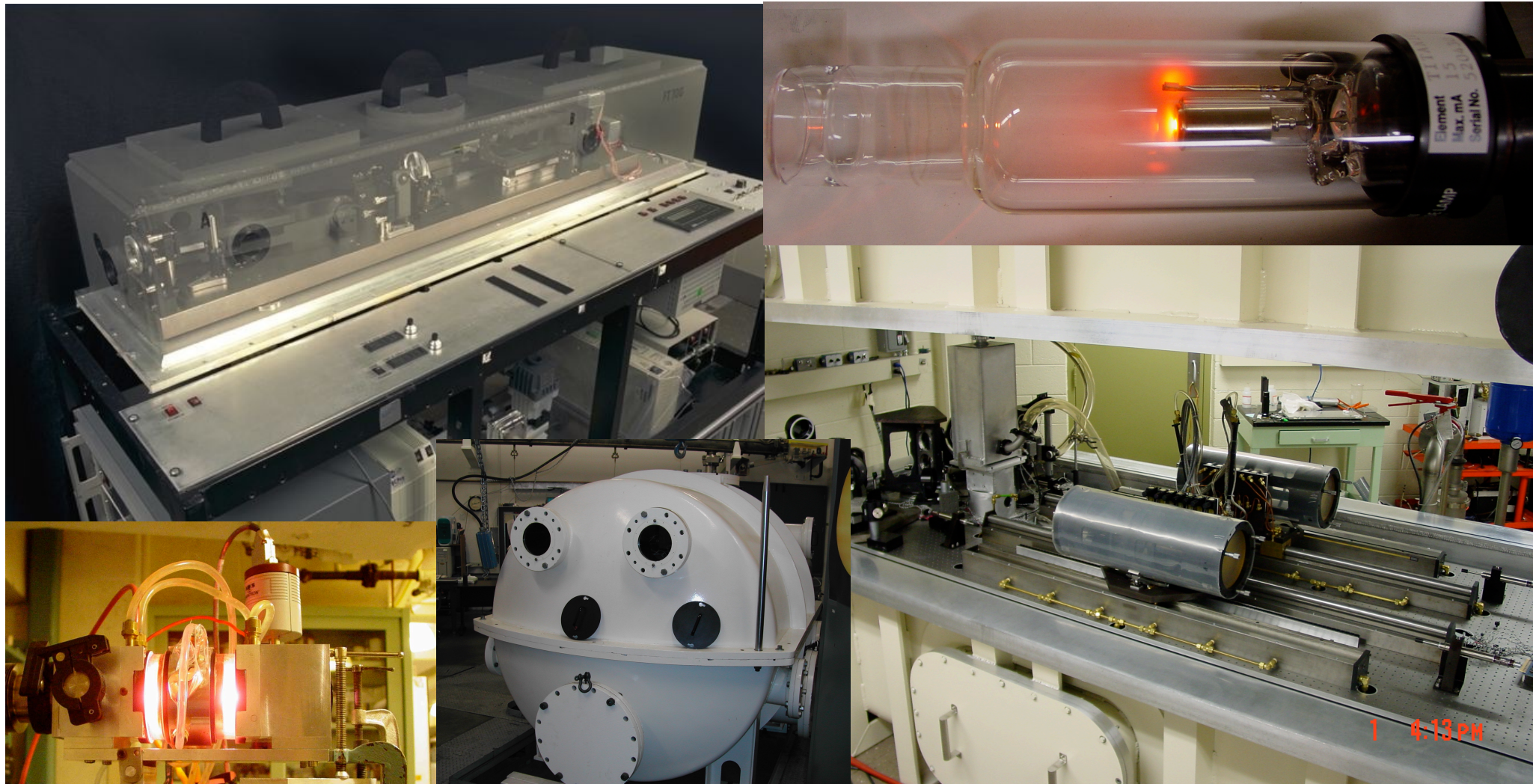


# Measurements of branching fractions using Fourier transform and grating spectroscopy

- with a diversion to wavelength standards



# Jim's contribution to oscillators strengths

111 papers in NIST's atomic spectra bibliographic database by Jim as author or co-author

Cover substantial part of periodic table:

<sup>1</sup> H	I																<sup>2</sup> He	
<sup>3</sup> Li	<sup>4</sup> Be	II										<sup>5</sup> B	<sup>6</sup> C	<sup>7</sup> N	<sup>8</sup> O	<sup>9</sup> F	<sup>10</sup> Ne	
<sup>11</sup> Na	<sup>12</sup> Mg	I&II										<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S	<sup>17</sup> Cl	<sup>18</sup> Ar	
<sup>19</sup> K	<sup>20</sup> Ca	<sup>21</sup> Sc	<sup>22</sup> Ti	<sup>23</sup> V	<sup>24</sup> Cr	<sup>25</sup> Mn	<sup>26</sup> Fe	<sup>27</sup> Co	<sup>28</sup> Ni	<sup>29</sup> Cu	<sup>30</sup> Zn	<sup>31</sup> Ga	<sup>32</sup> Ge	<sup>33</sup> As	<sup>34</sup> Se	<sup>35</sup> Br	<sup>36</sup> Kr	
<sup>37</sup> Rb	<sup>38</sup> Sr	<sup>39</sup> Y	<sup>40</sup> Zr	<sup>41</sup> Nb	<sup>42</sup> Mo	<sup>43</sup> Tc	<sup>44</sup> Ru	<sup>45</sup> Rh	<sup>46</sup> Pd	<sup>47</sup> Ag	<sup>48</sup> Cd	<sup>49</sup> In	<sup>50</sup> Sn	<sup>51</sup> Sb	<sup>52</sup> Te	<sup>53</sup> I	<sup>54</sup> Xe	
<sup>55</sup> Cs	<sup>56</sup> Ba	*	<sup>72</sup> Hf	<sup>73</sup> Ta	<sup>74</sup> W	<sup>75</sup> Re	<sup>76</sup> Os	<sup>77</sup> Ir	<sup>78</sup> Pt	<sup>79</sup> Au	<sup>80</sup> Hg	<sup>81</sup> Tl	<sup>82</sup> Pb	<sup>83</sup> Bi	<sup>84</sup> Po	<sup>85</sup> At	<sup>86</sup> Rn	
<sup>87</sup> Fr	<sup>88</sup> Ra	+																
* Lanthanides		<sup>57</sup> La	<sup>58</sup> Ce	<sup>59</sup> Pr	<sup>60</sup> Nd	<sup>61</sup> Pm	<sup>62</sup> Sm	<sup>63</sup> Eu	<sup>64</sup> Gd	<sup>65</sup> Tb	<sup>66</sup> Dy	<sup>67</sup> Ho	<sup>68</sup> Er	<sup>69</sup> Tm	<sup>70</sup> Yb	<sup>71</sup> Lu		
+ Actinides		<sup>89</sup> Ac	<sup>90</sup> Th	<sup>91</sup> Pa	<sup>92</sup> U	<sup>93</sup> Np	<sup>94</sup> Pu	<sup>95</sup> Am	<sup>96</sup> Cm	<sup>97</sup> Bk	<sup>98</sup> Cf	<sup>99</sup> Es						

# Babar comes to Kitt Peak - and so does Jim

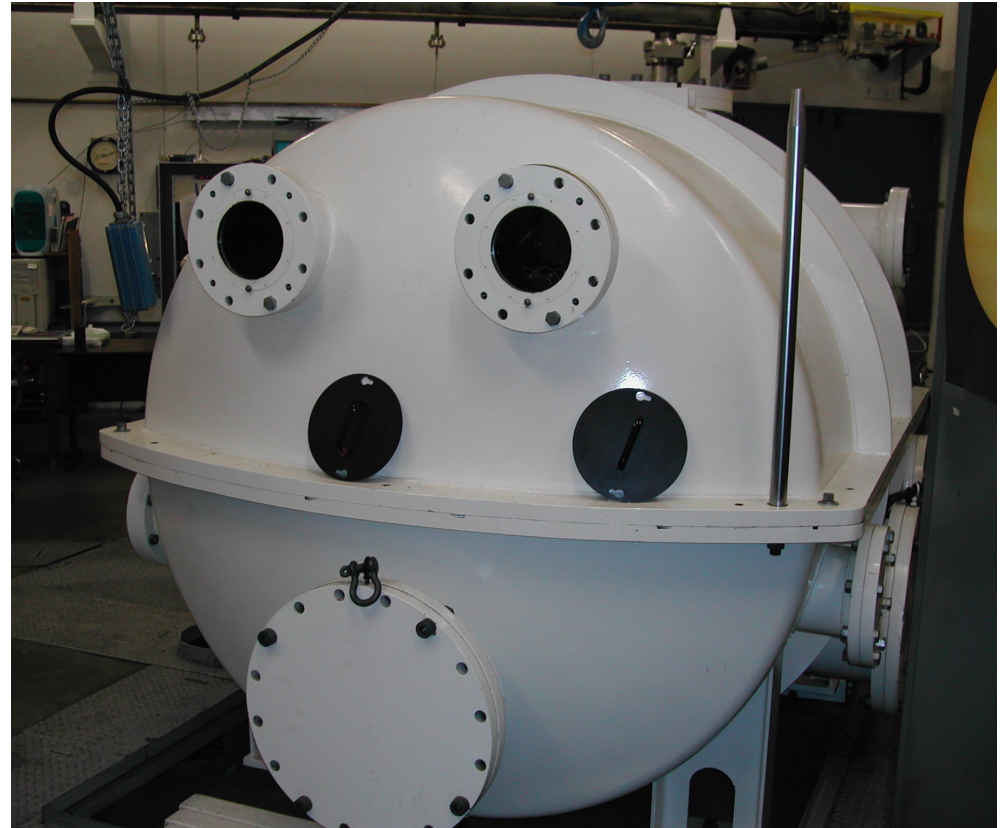
- Observes whole spectrum at once, so drift in light source doesn't matter.
- Immune to scattered light.
- High resolution and accuracy
- Large number of lines observed simultaneously.

Several hundred of spectra in NSO archive were measured by Jim, starting in mid-1980's.

First one I found was of Nb hcl in March, 1984:

“Absolute transition probabilities in Nb I and Hf I and a solution to the problem of missing infrared branches”, 1986, D.W.Duquette,

E.A.Den Hartog, J.E.Lawler, J. Quant. Spectr. Rad. Transfer 35, 281

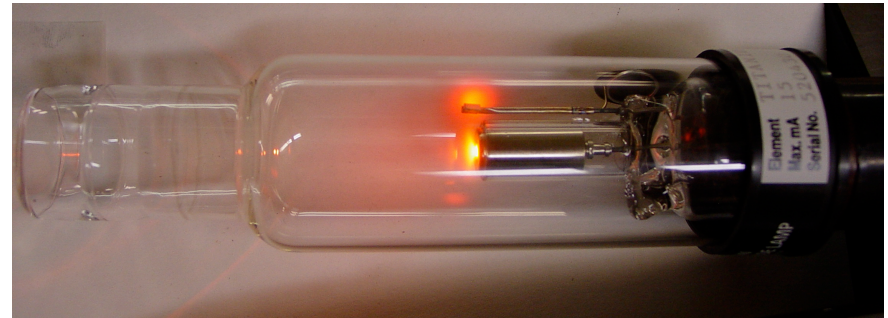


## Branching fractions using FTS

- Use low current lamps – easy to transport and set up at remote sites
- Calibrate with argon branching ratios – eliminates complications of using standard lamps.

Techniques go together, as the Ar branching ratios automatically include the window.

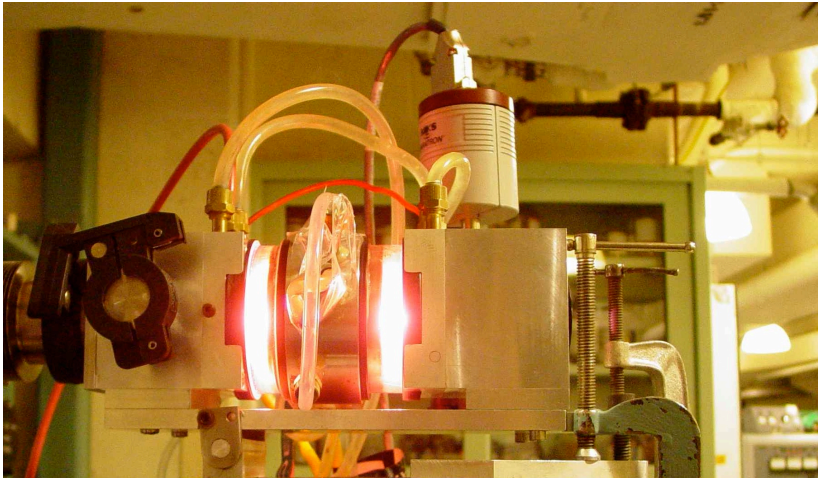
Relies on measurements of Whaling & others – how well were these calibrated?



# 2-m FTS at NIST



# Branching fractions at NIST

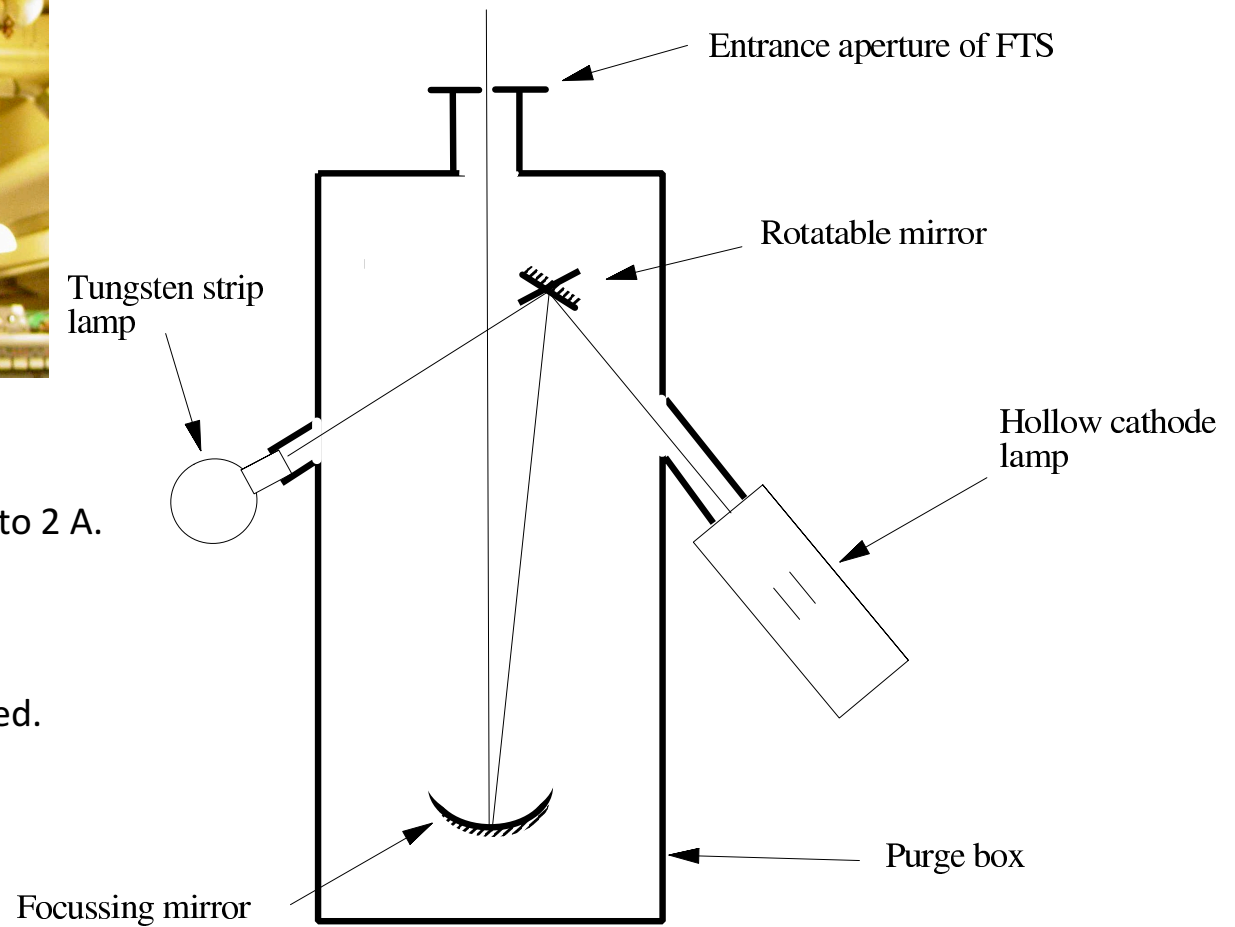


T-setup used to obtain calibrated spectra of a hollow cathode lamp

High current hollow cathode lamp – run at up to 2 A.

Calibrated with standard lamps

Separate measurement of lamp window needed.



## Branching fractions in Dy I and Dy II

EPRI funded project to measure RE elements for lighting

### UW

- FTS measurements at KPNO of low current hollow cathode lamps
- Calibrated with argon BRs

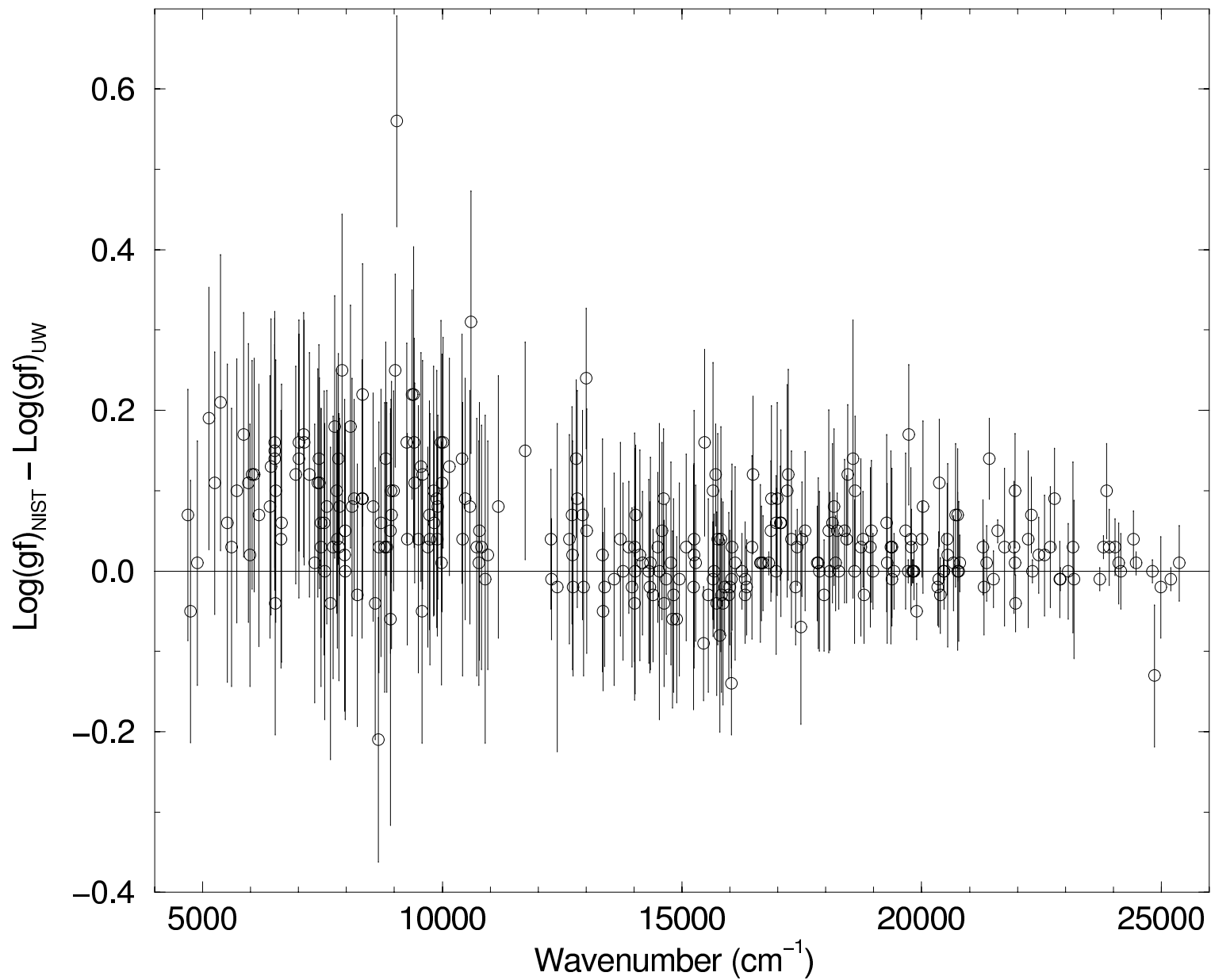
### NIST

- FTS measurements of high-current hcls (0.1 – 0.5 A)
- Calibrated with tungsten standard lamp.

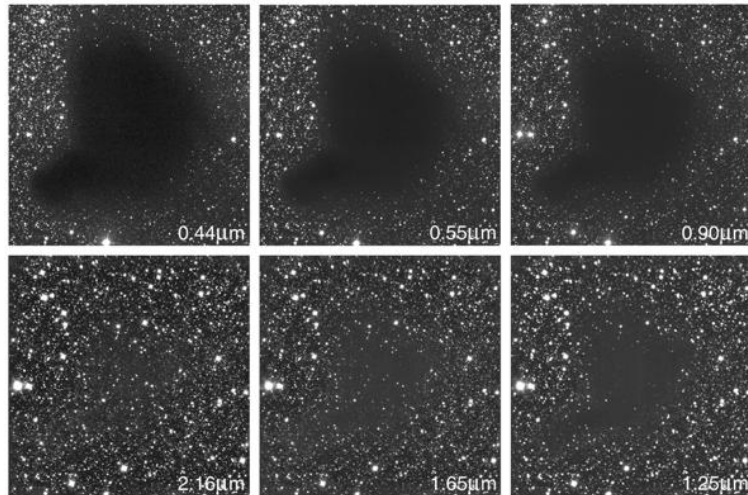
Transition probabilities for 915 lines measured.

So how did we do?

# Comparison of Dy branching fractions using both methods



# Why IR astronomical spectroscopy?



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

ESO PR Photo 29b/99 (2 July 1999)

© European Southern Observatory

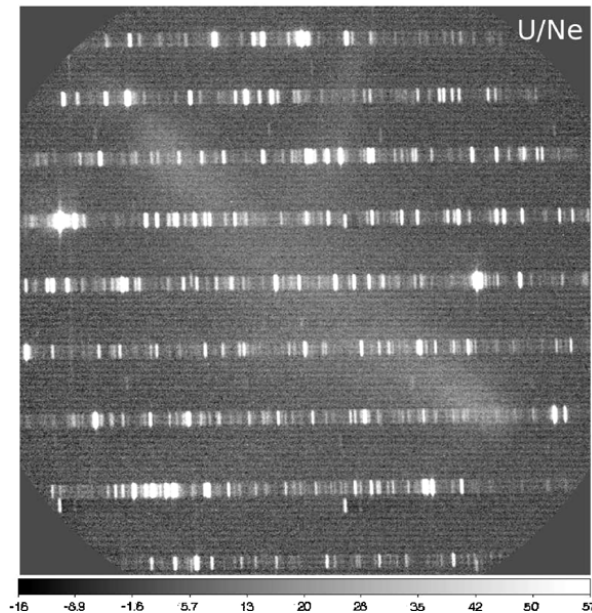
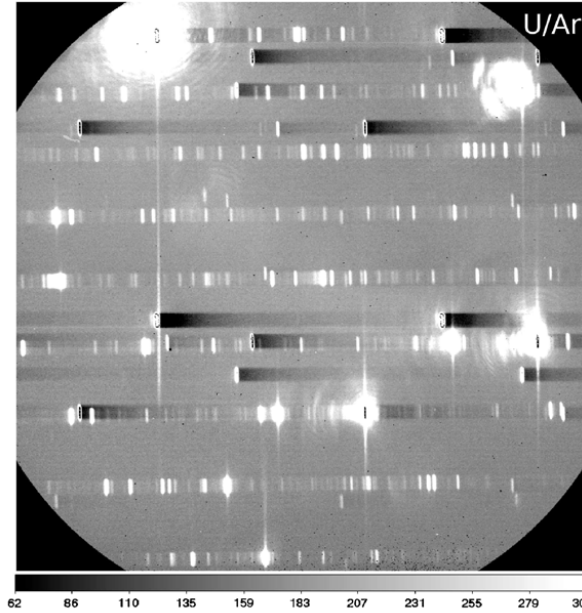
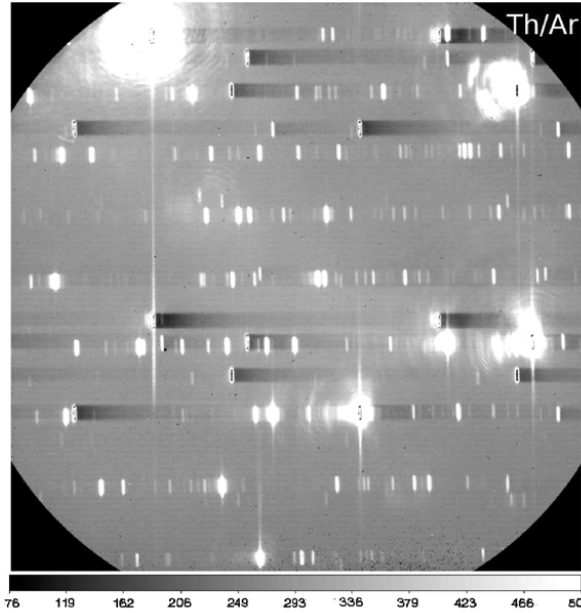


IR can penetrate dust clouds – to measure stellar abundances in galactic bulge, we need to look in IR.

APOGEE spectrograph (2011 – spring 2014) measured abundances of >100,000 giant stars throughout the Galaxy, including the dust-obscured bulge.

Images of a stellar birthplace – IR shows background stars that can be used to estimate dust content of cloud that will soon collapse to form a star.

# Comparison of Th and U in IR



Spectra of Th/Ar, U/Ar, and U/Ne hollow cathode lamps with Penn State Pathfinder Spectrograph—designed to look for exoplanets around cool stars (M-dwarfs) in the IR.

## THE INFRARED SPECTRUM OF URANIUM HOLLOW CATHODE LAMPS FROM 850 nm to 4000 nm: WAVENUMBERS AND LINE IDENTIFICATIONS FROM FOURIER TRANSFORM SPECTRA

STEPHEN L. REDMAN<sup>1,2</sup>, JAMES E. LAWLER<sup>3</sup>, GILLIAN NAVE<sup>2</sup>, LAWRENCE W. RAMSEY<sup>1,4</sup>, AND SUVRATH MAHADEVAN<sup>1,4</sup>

<sup>1</sup> Department of Astronomy & Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA

<sup>2</sup> National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

<sup>3</sup> Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, WI 53706, USA

<sup>4</sup> Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA

*Received 2011 May 26; accepted 2011 June 26; published 2011 August 4*

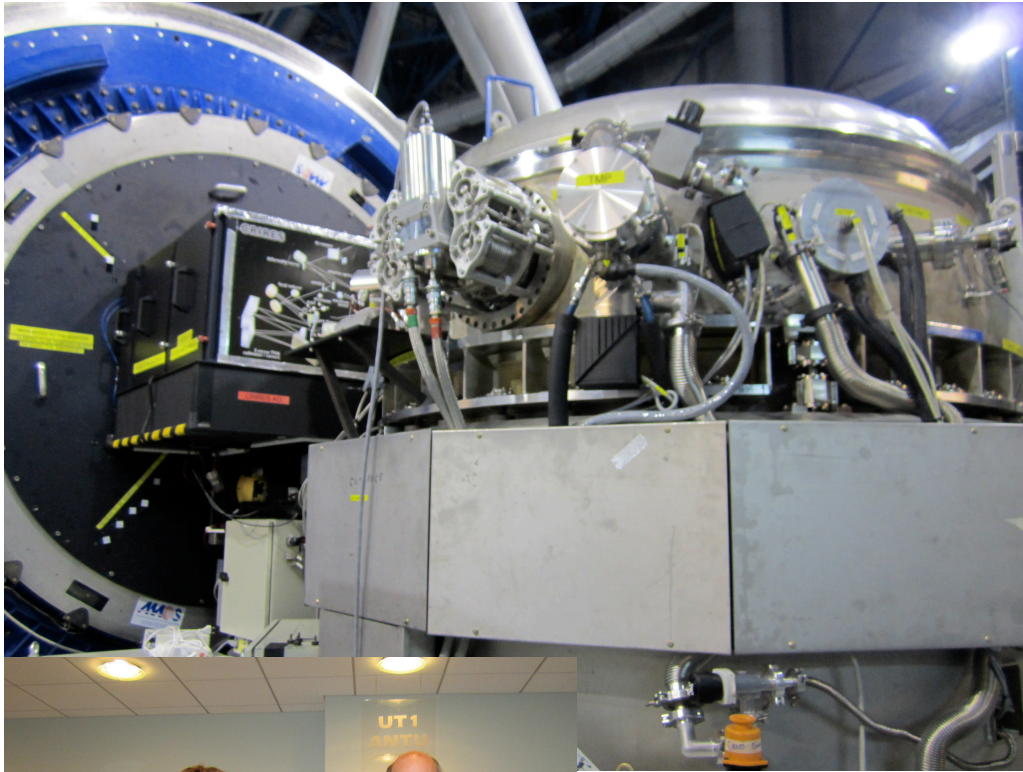
### ABSTRACT

We provide new measurements of wavenumbers and line identifications of 10,100 U I and U II near-infrared (NIR) emission lines between  $2500\text{ cm}^{-1}$  and  $12,000\text{ cm}^{-1}$  (4000–850 nm) using archival Fourier transform spectrometer spectra from the National Solar Observatory. This line list includes isolated uranium lines in the *Y*, *J*, *H*, *K*, and *L* bands (0.9–1.1  $\mu\text{m}$ , 1.2–1.35  $\mu\text{m}$ , 1.5–1.65  $\mu\text{m}$ , 2.0–2.4  $\mu\text{m}$ , and 3.0–4.0  $\mu\text{m}$ , respectively), and provides six times as many calibration lines as thorium in the NIR spectral range. The line lists we provide enable inexpensive, commercially available uranium hollow cathode lamps to be used for high-precision wavelength calibration of existing and future high-resolution NIR spectrographs.

*Key words:* astronomical databases: miscellaneous – atomic data – line: identification – standards

*Online-only material:* color figure, machine-readable table

# Uranium lamps at the VLT



Steven & Jonathon Smoker at the VLT control room.

New atlas in preparation for CRIRES+



# Oscillator strengths in Cr II

New oscillator strengths for Cr II:

One spectrum taken to confirm calibration, not in paper.

Focus on weak lines – used 2 spectra from echelle.

Radiometric standard lamps recalibrated, estimate of window transmission made, gain-dependent spectral response of detectors (M. Wood).

Table 2  
Fourier Transform Spectra of Custom Water-cooled Hollow Cathode Discharge (HCD) and a Penning Discharge (Index 17) Lamp

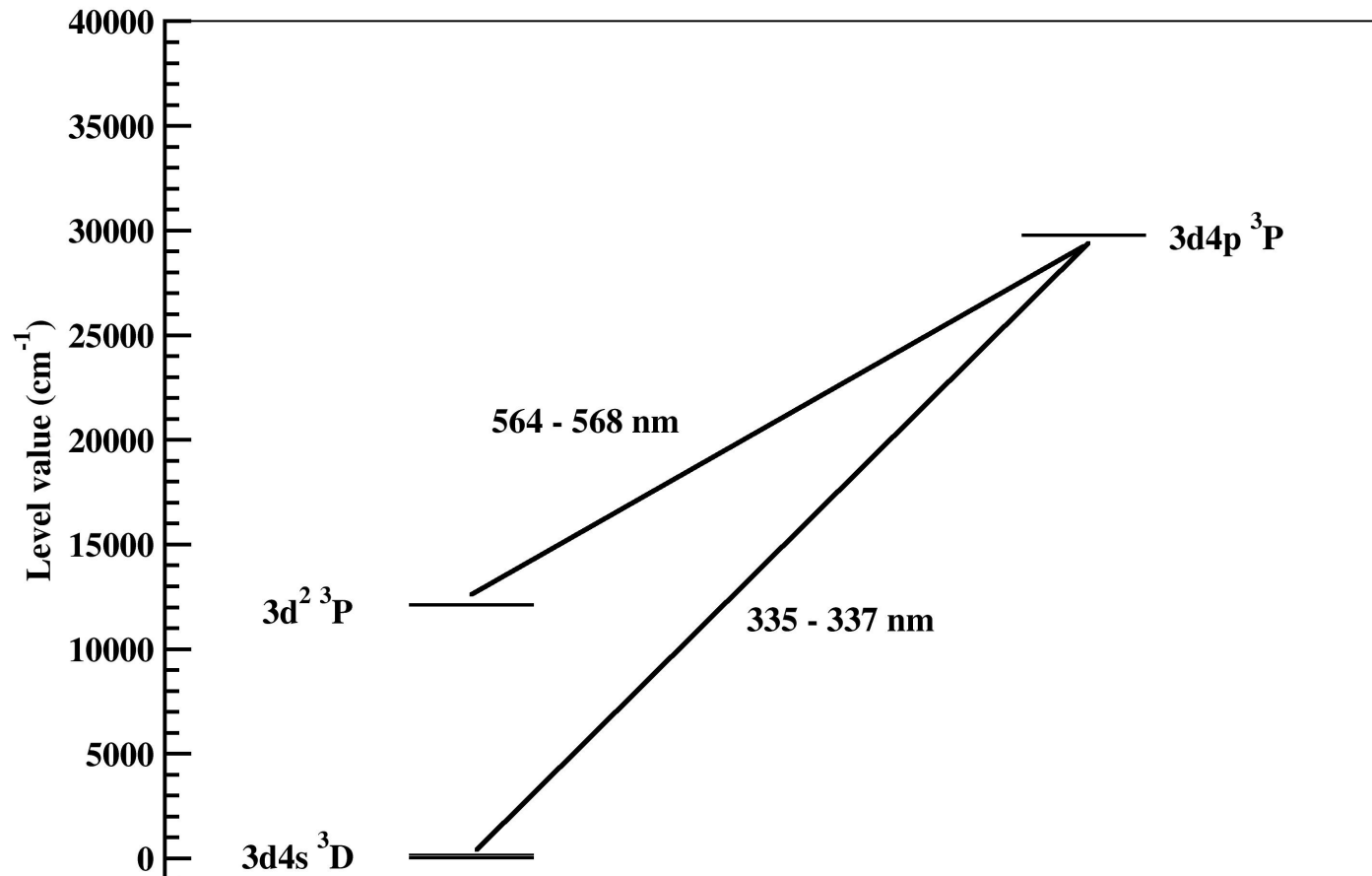
Index #	Year, Day	Serial #	FTS	Buffer Gas and Pressure (mmHg)	Lamp Current (mA)	Wave Number Range (cm <sup>-1</sup> )	Limit of Resolution (cm <sup>-1</sup> )	Coadds	Beam Splitter	Filter and Detector <sup>a</sup>	Relative Radiometric Calibration
1	1982 Jun 25	7	NSO 1 m FTS	Ar 0.65	500	7664–44591	0.057	8	UV	CS9-54 filter and Mid Range Si PD	Ar II lines
2	1982 Jun 26	4	NSO 1 m FTS	Ar 1.0	100	7664–44591	0.057	6	UV	CS9-54 filter and Mid Range Si PD	Ar II lines
3	1984 Jul 26	6	NSO 1 m FTS	Ne 3.0	750	7982–45407	0.054	4	UV	NSF and R166 PMT, WG295 filter and Mid Range Si PD	W-filament, piecewise flat in UV
4	1984 Jul 26	7	NSO 1 m FTS	Ne 3.3	1500	7982–45407	0.054	4	UV	NSF and R166 PMT, WG295 filter and Mid Range Si PD	W-filament, piecewise flat in UV
5	1984 Jul 26	8	NSO 1 m FTS	Ne 3.3	1500	7982–45407	0.054	4	UV	NSF and R166 PMT, WG295 filter and Mid Range Si PD	W-filament, piecewise flat in UV
6	1980 Feb 28	1	NSO 1 m FTS	Ar 2.5	500	7908–28921	0.035	4	Vis	GG375 filter and SB Si PD	Ar II lines
7	1980 Mar 25	3	NSO 1 m FTS	Ne 4.0	950	13489–27089	0.034	10	Vis	GG400 + CS4-96 filters and SB Si PD	W-filament
8	1982 Jun 25	6	NSO 1 m FTS	Ne 2.0	500	7664–44591	0.057	9	UV	CS9-54 filter and Mid Range Si PD	piecewise flat
9	1982 Jun 25	8	NSO 1 m FTS	Ne 1.2	500	7664–44591	0.057	8	UV	CS9-54 filter and Mid Range Si PD	piecewise flat
10	1984 Jul 26	11	NSO 1 m FTS	Ne 2.6	500	7982–45407	0.054	8	UV	NSF and R166 PMT, WG295 and Mid Range Si PD	piecewise flat
11	2000 Nov 6	1	NIST FT700	Ar 0.65	1500	22000–44000	0.033	64	CaF2	UG11 1 mm filter and R106UH PMT (350s cathode)	Ar II lines
12	2000 Nov 6	2	NIST FT700	Ar 0.65	200	22000–44000	0.033	64	CaF2	UG11 1 mm filter and R106UH PMT (350s cathode)	Ar II lines
13	2000 Nov 16	1	NIST FT700	Ar 0.66	1500	19000–38000	0.027	64	CaF2	BG4 filter and R106UH PMT (350s cathode)	W-filament
14	2000 Nov 15	2	NIST FT700	Ar 0.66	700	19000–38000	0.030	32	CaF2	BG4 filter and R106UH PMT (350s cathode)	W-filament
15	2000 Nov 15	1	NIST FT700	Ar 0.65	200	19000–38000	0.030	32	CaF2	BG4 filter and R106UH PMT (350s cathode)	W-filament
16	2000 Oct 26	1	NIST FT700	Ne 0.5	700	28000–56000	0.050	64	CaF2	NSF and R7154 PMT (250s cathode)	piecewise flat
17	2000 Dec 8	1	NIST FT700	Ne 0.003	1400	28000–56000	0.150	128	CaF2	NSF and R7154 PMT (250s cathode)	piecewise flat
18	2011 Jun 10	7	NIST 2 m FTS	Ne 3.0	2000	0–35000	0.020	107	FS	NSF and Large area Si PD	W-filament

Notes. Spectra were recorded using the 1 m FTS on the McMath telescope at the NSO, Kitt Peak, AZ, and the VUV Chelsea Instruments FT700 and the 2 m Optical FTS at NIST, Gaithersburg, MD.  
<sup>a</sup> Detector types include the Super Blue (SB) Si photodiode (PD), Mid Range Si PD, and R166 photomultiplier (PMT) at NSO. Detector types at NIST include R106UH PMT, R7154 PMT, and Large area Si PD. The UV beam splitter at NSO is fused silica (FS). Filter numbers (Schott and Corning) are listed and NSF means No Spectral Filter. There are two output ports on an FTS and occasionally two different detector/filter combinations are used for a single spectrum.

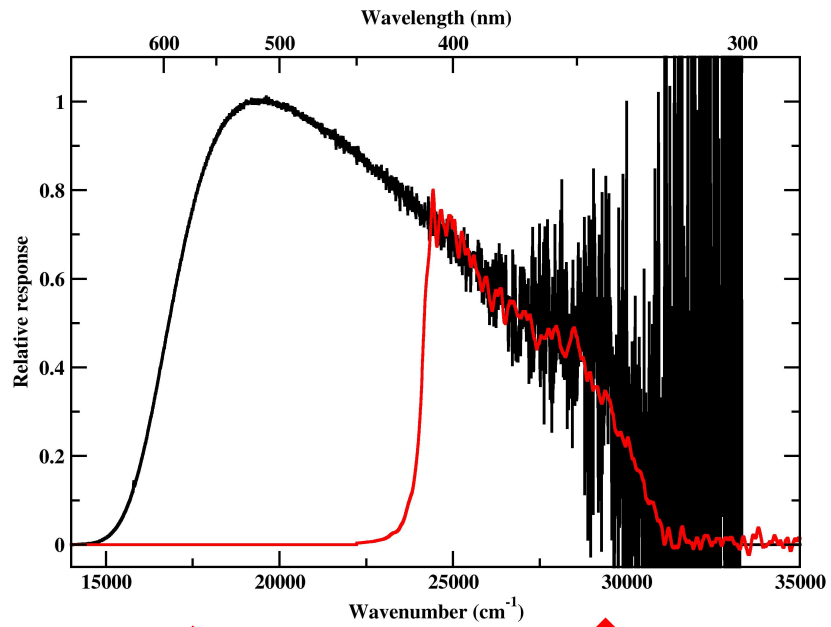
Still no visit from Jim to NIST – these are all archival spectra.  
 - But I did get Mike!

## Sc II – Jim’s first measurements at NIST (2015)

Lines of Sc II near 566 nm are valuable for determining the abundance of scandium in stars. The upper level of these lines also decays to the ground term through lines near 336 nm. The branching fractions of these lines are tricky to measure as they span a range where laboratory spectra need to be calibrated with two different standard lamps that have a small region of overlap.



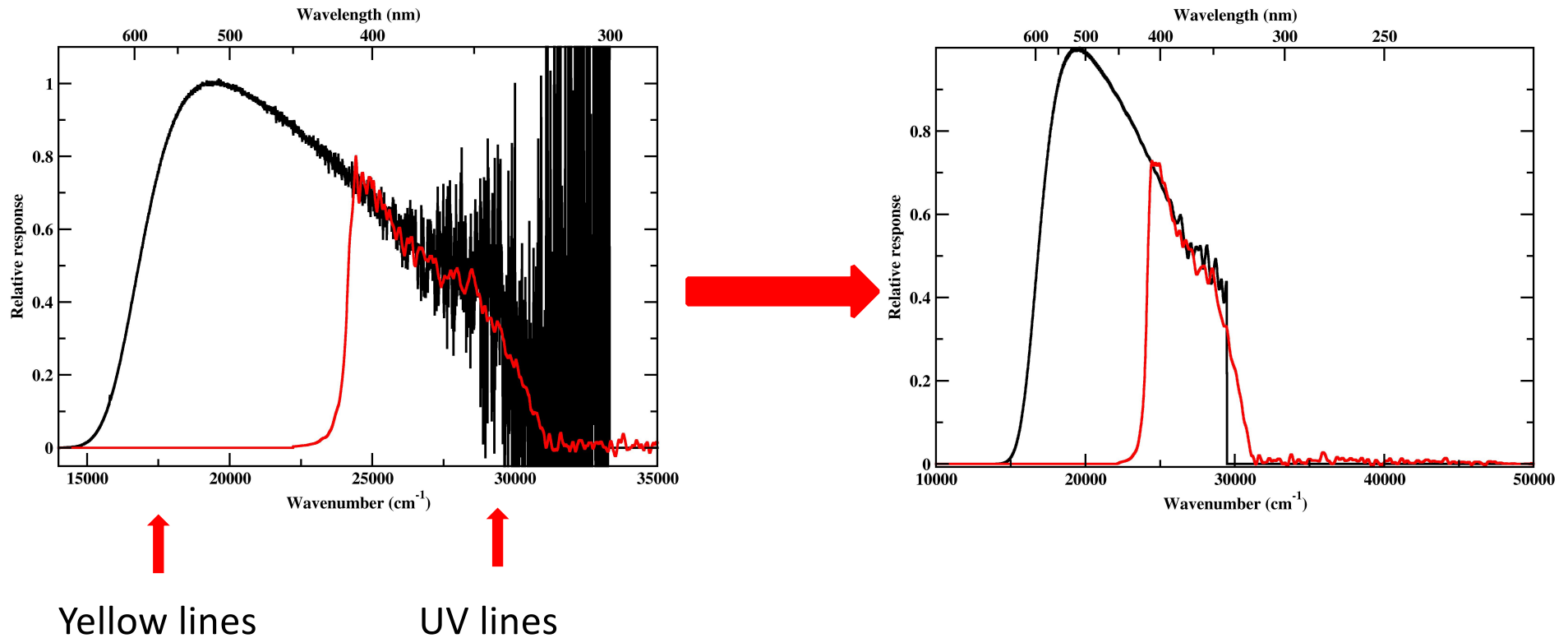
# Filtering response function to improve overlap



Yellow lines

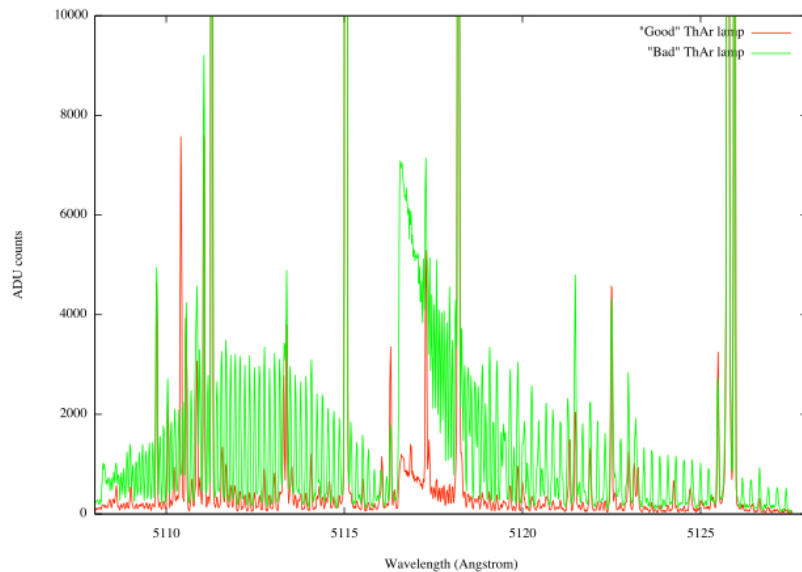
UV lines

# Filtering response function to improve overlap



Ar branching ratios need to match the rapid change in the response of the FTS.

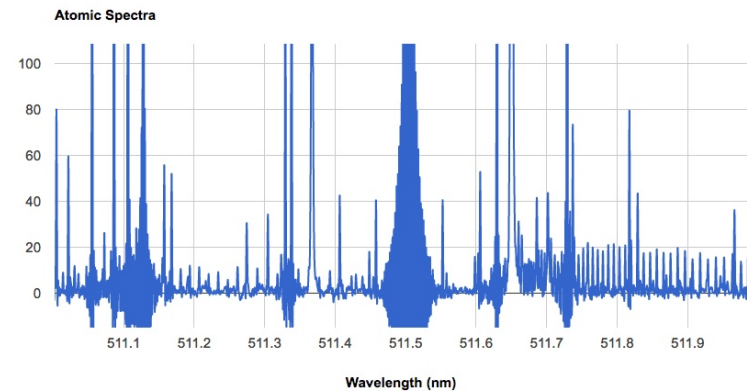
# ThO contamination of Th/Ar lamps used for astronomical spectrograph calibration



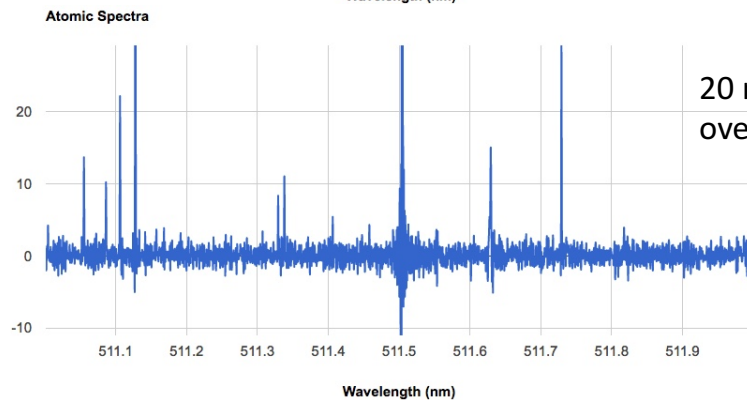
HARPS spectrum of Th lamp (10 mA)

Red: old lamp

Green: New lamp



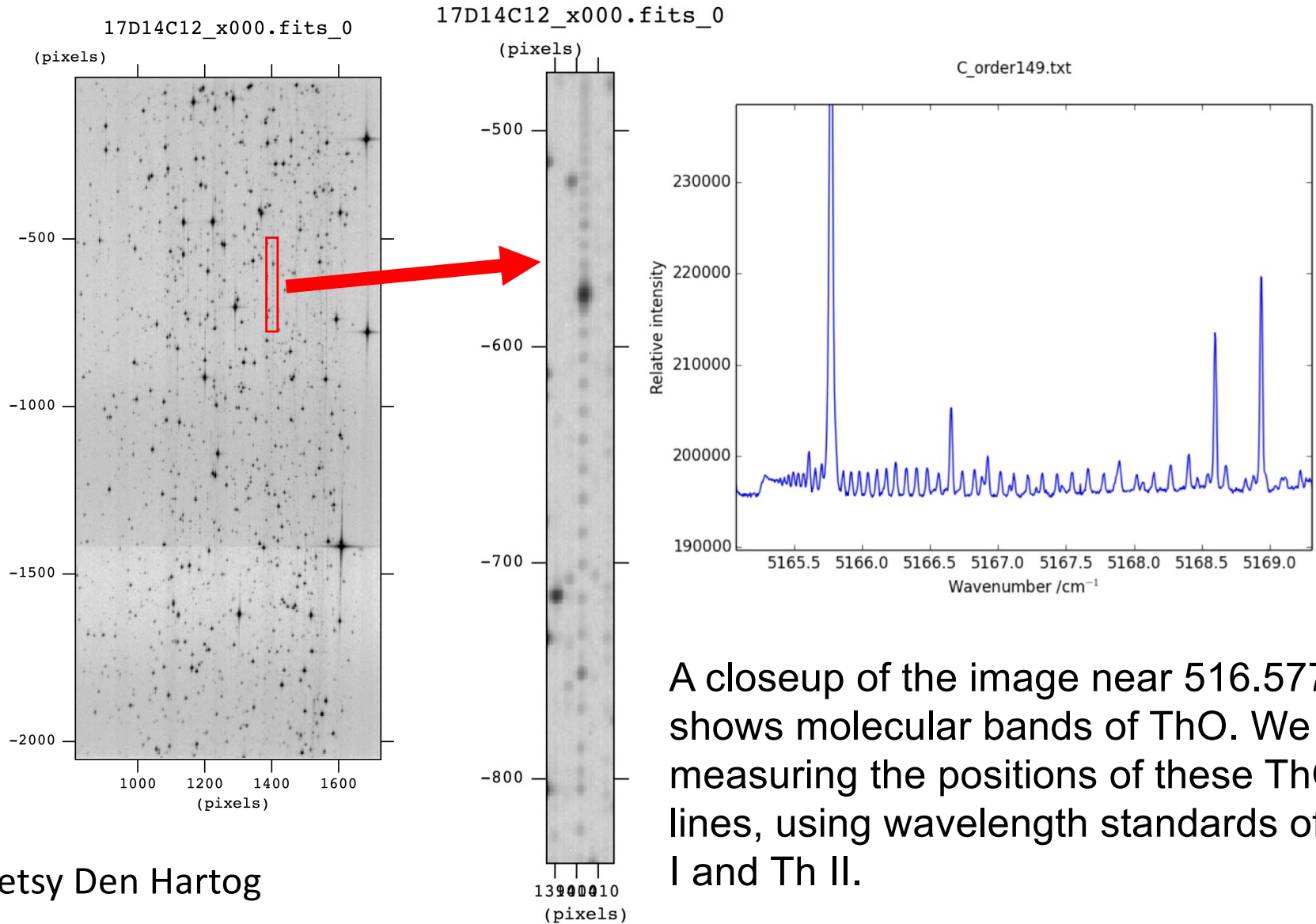
75mA, Palmer & Engleman atlas.



20 mA FTS spectrum with over 20 h integration!

FTS has lower sensitivity because of higher resolution, single detector, and redistribution of noise from strong lines across whole spectrum. Echelle spectrograph with array detector can win on SNR.

# Solution: High resolution Echelle



Betsy Den Hartog

A closeup of the image near 516.577 nm shows molecular bands of ThO. We are measuring the positions of these ThO lines, using wavelength standards of Th I and Th II.

# Conclusions

- Archival spectra have incredible value beyond their original purpose
- Both standard lamps and Ar branching ratios can be used for radiometric calibration, with a combination of techniques gives best results
- Combination of FTS and echelle gives high sensitivity and wavelength resolution needed for complex blends.

# Jim's contribution to oscillators strengths

<sup>1</sup> H	<b>I</b>																<sup>2</sup> He	
<sup>3</sup> Li	<sup>4</sup> Be	<b>II</b>										<sup>5</sup> B	<sup>6</sup> C	<sup>7</sup> N	<sup>8</sup> O	<sup>9</sup> F	<sup>10</sup> Ne	
<sup>11</sup> Na	<sup>12</sup> Mg	<b>I&amp;II</b>										<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S	<sup>17</sup> Cl	<sup>18</sup> Ar	
<sup>19</sup> K	<sup>20</sup> Ca	<sup>21</sup> Sc	<sup>22</sup> Ti	<sup>23</sup> V	<sup>24</sup> Cr	<sup>25</sup> Mn	<sup>26</sup> Fe	<sup>27</sup> Co	<sup>28</sup> Ni	<sup>29</sup> Cu	<sup>30</sup> Zn	<sup>31</sup> Ga	<sup>32</sup> Ge	<sup>33</sup> As	<sup>34</sup> Se	<sup>35</sup> Br	<sup>36</sup> Kr	
<sup>37</sup> Rb	<sup>38</sup> Sr	<sup>39</sup> Y	<sup>40</sup> Zr	<sup>41</sup> Nb	<sup>42</sup> Mo	<sup>43</sup> Tc	<sup>44</sup> Ru	<sup>45</sup> Rh	<sup>46</sup> Pd	<sup>47</sup> Ag	<sup>48</sup> Cd	<sup>49</sup> In	<sup>50</sup> Sn	<sup>51</sup> Sb	<sup>52</sup> Te	<sup>53</sup> I	<sup>54</sup> Xe	
<sup>55</sup> Cs	<sup>56</sup> Ba	*	<sup>72</sup> Hf	<sup>73</sup> Ta	<sup>74</sup> W	<sup>75</sup> Re	<sup>76</sup> Os	<sup>77</sup> Ir	<sup>78</sup> Pt	<sup>79</sup> Au	<sup>80</sup> Hg	<sup>81</sup> Tl	<sup>82</sup> Pb	<sup>83</sup> Bi	<sup>84</sup> Po	<sup>85</sup> At	<sup>86</sup> Rn	
<sup>87</sup> Fr	<sup>88</sup> Ra	+																
* Lanthanides		<sup>57</sup> La	<sup>58</sup> Ce	<sup>59</sup> Pr	<sup>60</sup> Nd	<sup>61</sup> Pm	<sup>62</sup> Sm	<sup>63</sup> Eu	<sup>64</sup> Gd	<sup>65</sup> Tb	<sup>66</sup> Dy	<sup>67</sup> Ho	<sup>68</sup> Er	<sup>69</sup> Tm	<sup>70</sup> Yb	<sup>71</sup> Lu		
+ Actinides		<sup>89</sup> Ac	<sup>90</sup> Th	<sup>91</sup> Pa	<sup>92</sup> U	<sup>93</sup> Np	<sup>94</sup> Pu	<sup>95</sup> Am	<sup>96</sup> Cm	<sup>97</sup> Bk	<sup>98</sup> Cf	<sup>99</sup> Es						

**Rare earths (and actinides) are back in fashion!**