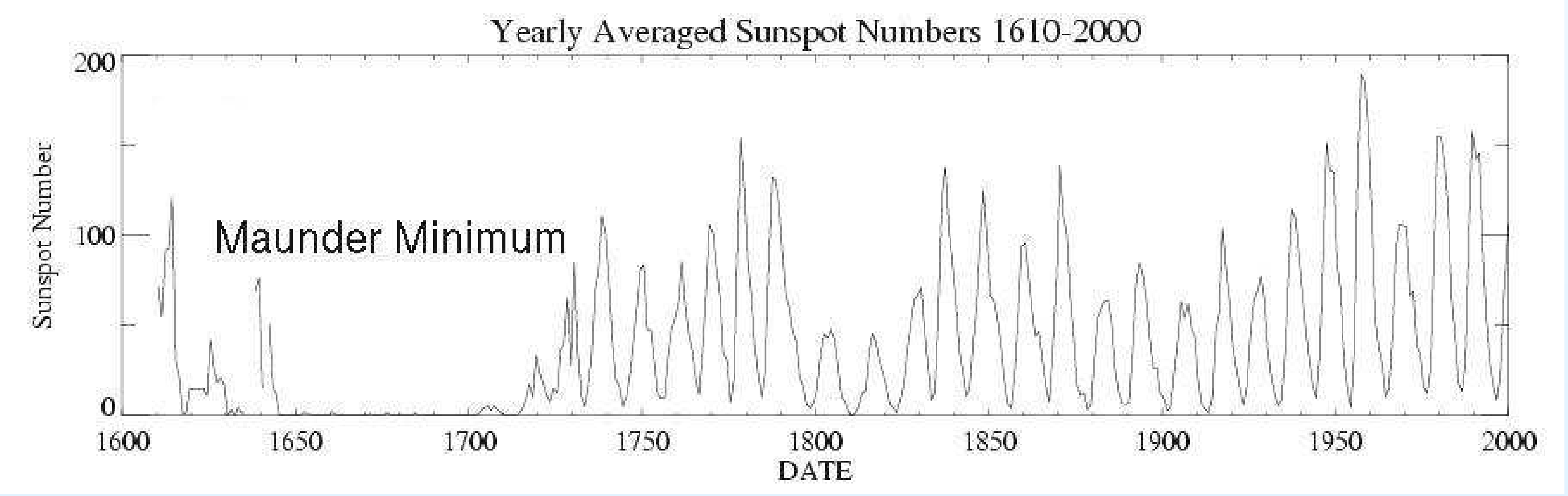
The solar chromosphere and corona during the Maunder Minimum

Philip G. Judge, High Altitude Observatory, NCAR,

Steven H. Saar, Harvard-Smithsonian Center for Astrophysics



The problem

- The Maunder Minimum (1645-1715) is the only documented period in which a correlation between climate and solar magnetic activity has been found (e.g., Eddy 1976).
- Very few sunspots were observed, nearly all of them in one hemisphere, yet
- ^{10}Be ice core records (e.g., Beer 2000) indicate continued modulation of cosmic rays by heliospheric magnetic fields.
- Question: *What happened to the solar magnetic dynamo during the Maunder Minimum?* We will never know for certain. Since chromospheric and coronal emission is related to surface magnetic fields, using stellar data, we ask
- *what was the probable state of the Sun's chromosphere and corona during this period?*

$\longrightarrow$ cycling dynamo

The solar Maunder Minimum in the stellar context

- Baliunas and colleagues have identified “flat–activity” solar-like stars in the Mt. Wilson Ca II survey;
- These stars are non-cycling and are very weakly active (Ca II S-index $\lesssim S$ values at solar cycle minima);
- Not all these stars are old- age indicators suggest that these stars may be in stellar “Grand Minima”.
- Early observations of Baliunas & Jastrow (1990) suggested a bimodal distribution of S indices:
    - flat activity stars occupy low S-index region
    - cycling ($\sim$ current Sun) occupy higher region
- White et al. (1992), concluded that *not even magnetic network was present during the Maunder Minimum, if Baliunas & Jastrow’s data are taken at face value.* The bimodal distribution has been called into question (Hall & Lockwood 2004; see below)

Methods

In inactive stars, magnetic contributions to Ca II emission are relatively small. Following Saar (1998), we look to far-UV and soft X-rays to reveal clearer signatures of magnetic activity:

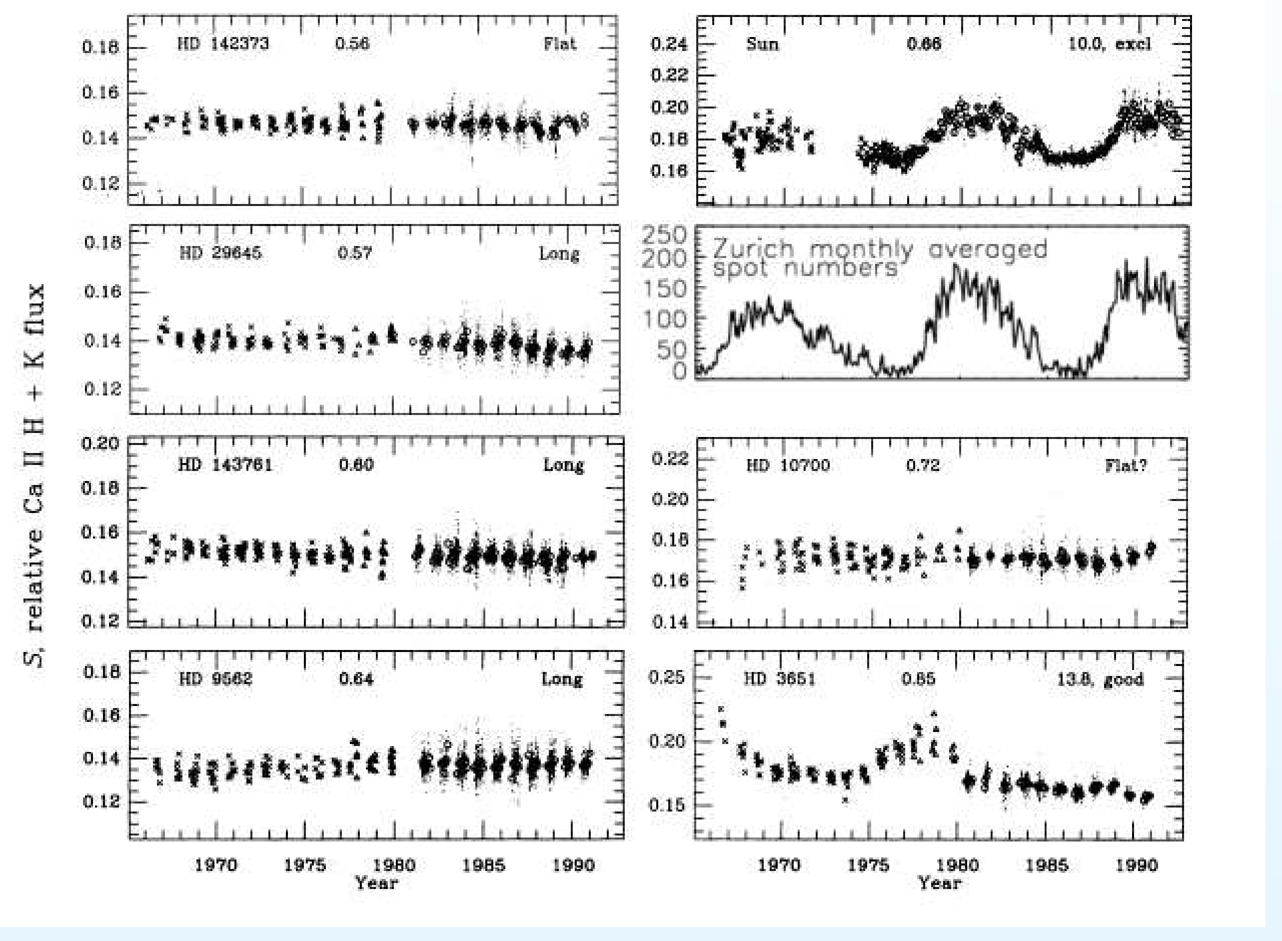
- with Ayres and Carlsson, we have acquired and analyzed
  - medium resolution (40,000) HST/STIS data of the flat activity star τ Cet (G8 V)
  - high resolution (100,000) HST/STIS data of the solar analog α Cen A
- we have analyzed low resolution ($\approx$2,000) HST/GHRS data acquired by Saar in 1995 of flat activity stars
- we have compared these data with carefully constructed “sun-as-a-star” UV data from the HRTS and SUMER instruments
- we have used a new estimate of solar cyclic ROSAT fluxes with formal errors $\pm 50\%$ (Judge et al. 2003)

Target stars

HD	name	V	$B-V$	spec.	$\langle S \rangle$	$\langle R'_{HK} \rangle$	notes
142373	χ Her	4.62	0.53	F9 V	0.147	-5.020	1.
29645		5.99	0.57	G3 V	0.140	-5.040	
143761	ρ CrB	5.40	0.60	G2 V	0.150	-5.106	2.
9562		5.76	0.64	G2 IV	0.136	-5.179	3.
...	Sun	-26.74	0.65	G2 V	0.16:0.2	-4.996:-4.799	4.
128620	α Cen A	0.0	0.69	G2 V	...	...	5.
10700	τ Cet	3.50	0.72	G8 V	0.171	-4.959	
3651	54 Psc	5.86	0.85	K0 V	$\approx$ 0.15	-5.100	6.

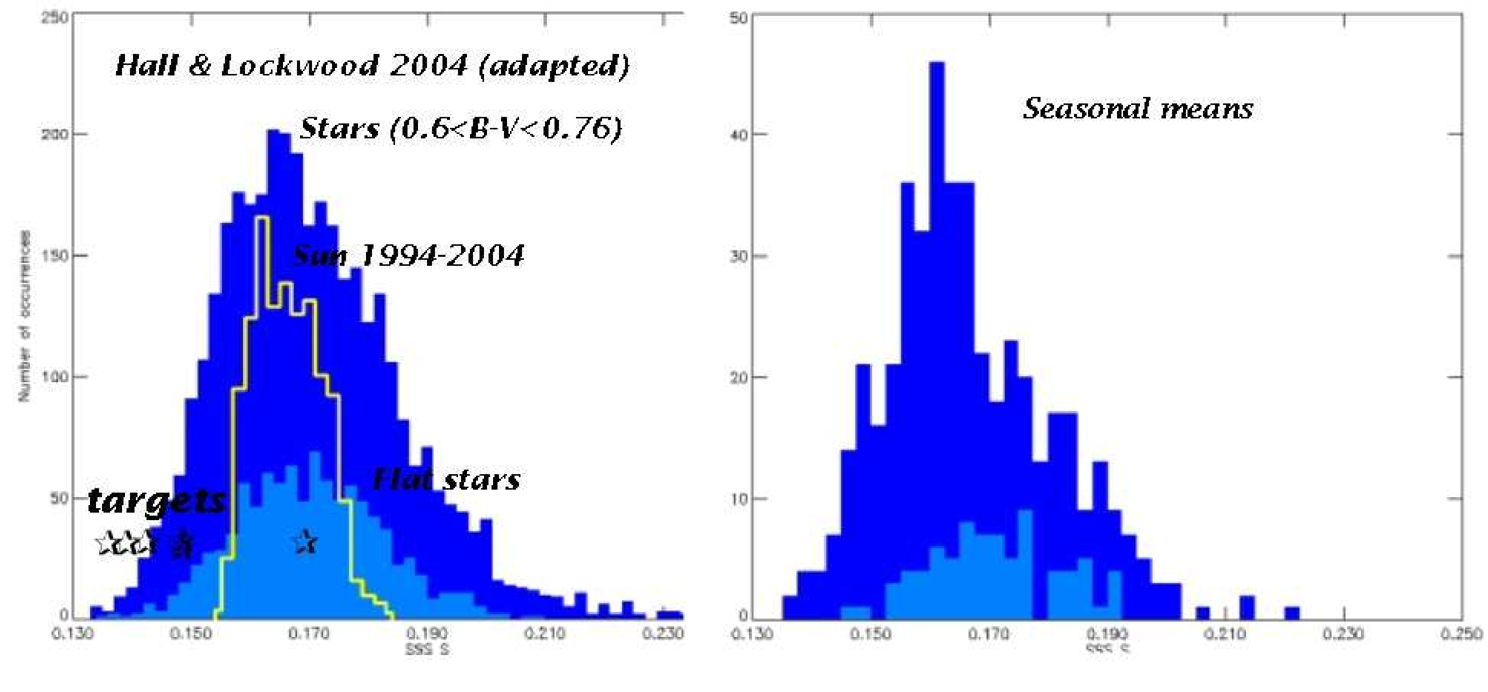
S indices from Baliunas et al. (1995), R'_{HK} values computed by one of us (SHS) 1. High RV star. 2. Recent secular rise (Hall 2004). 3. Large v sini? 4. S index gives typical values at solar minimum and maximum. 5. Solar analog. 6. Epoch 1990 S-value. Entering a grand minimum??

Target star Ca II S indices



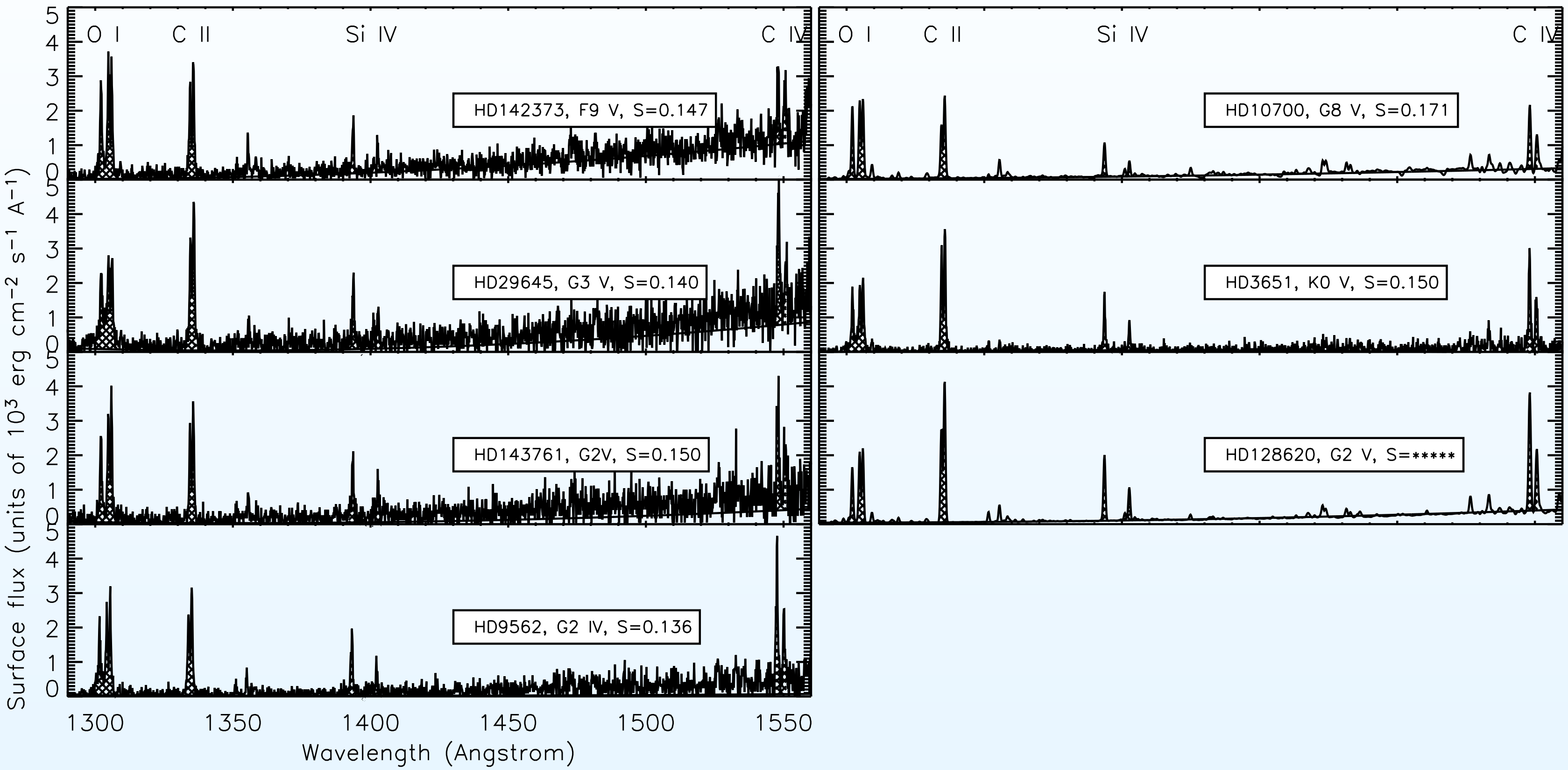
- Adapted from Baliunas et al. (1995)
- Figure also shows correlation of Ca II S index and sunspots

Target star Ca II S indices in the larger context



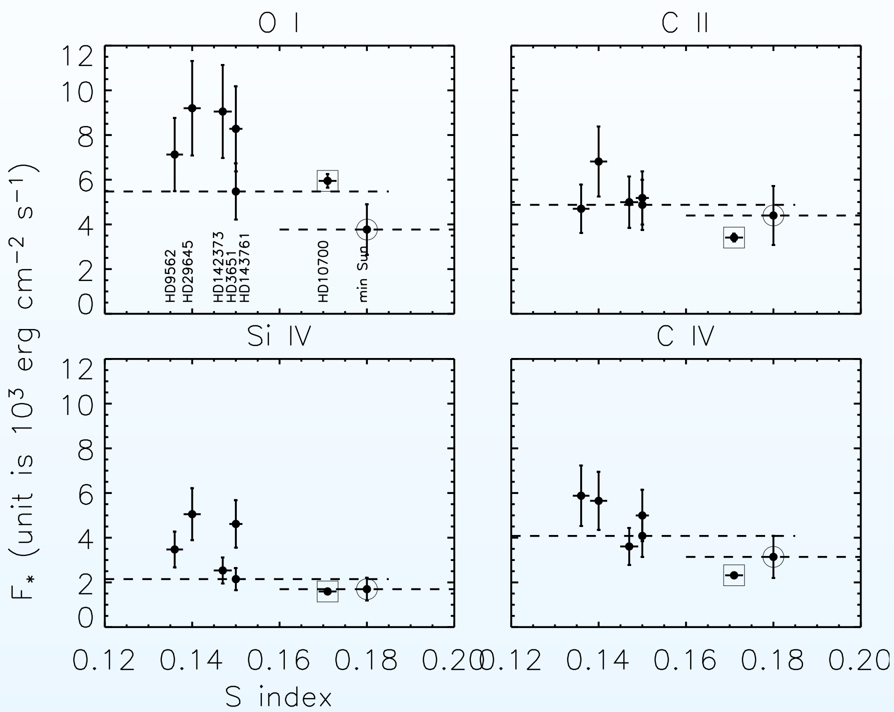
- Hall & Lockwood (2004); SSS data; normal distribution; solar-stellar uncertainty ΔS=0.004
- Differs from earlier bimodal distribution of Baliunas & Jastrow (1990):
  - Solar cycle minimum overlaps with “flat activity” stars, so
  - Using White et al. (1992) results, Maunder Minimum state admits significant surface magnetic fields

HST-GHRS data



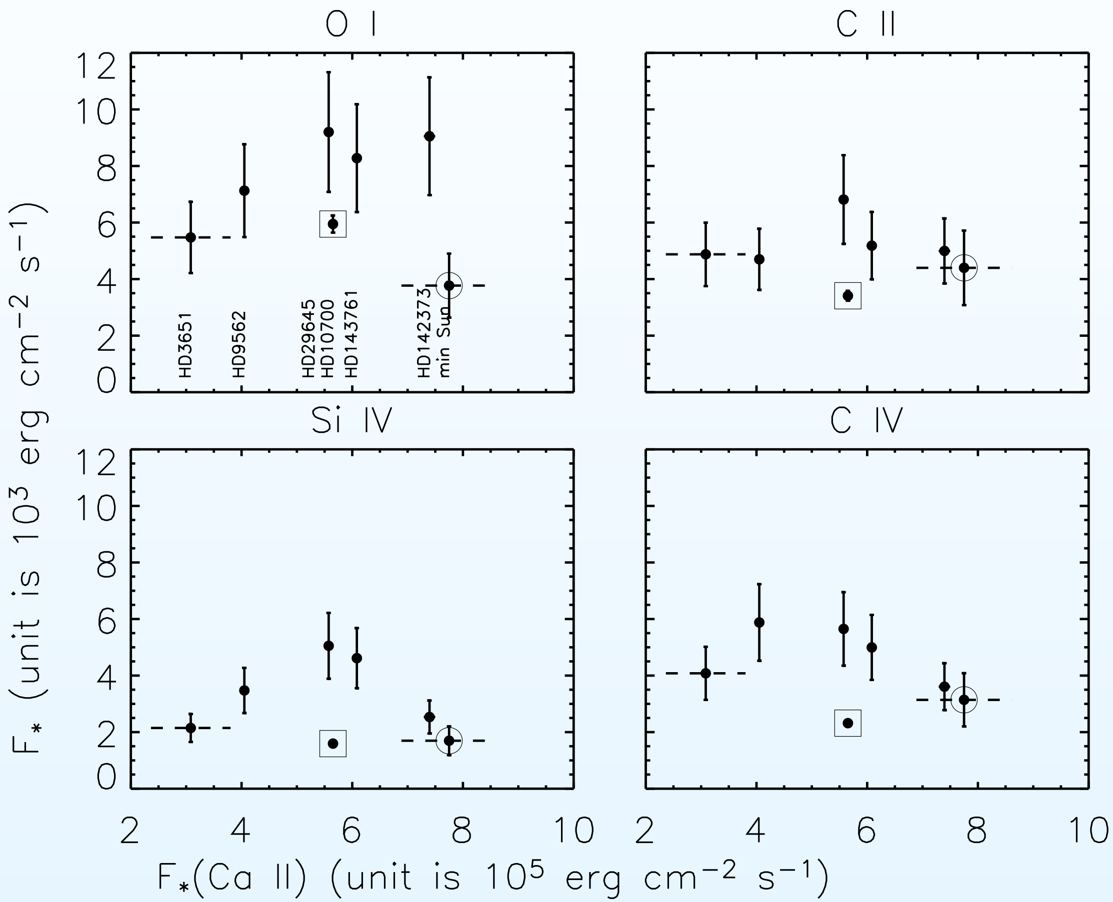
Low disperson GHRS data from 1995 (Saar). STIS data were convolved with the GHRS PSF for HD10700 (τ Ceti) and HD128620 (α Cen A). Surface flux uncertainties dominated for stars by Barnes-Evans relation (except τ Cet, α Cen A), and by SUMER absolute calibration (solar radiometry).

UV flux densities versus S-indices



- Solar minimum ($\odot$) and τ Ceti (boxed) data from Judge et al. (2004)
- RMS S values plotted from Baliunas et al. (1995); cycle amplitudes (dashed lines) are plotted for the Sun and HD 3651
- While many stars have S indices lower than τ Ceti,
- τ Ceti has the *lowest UV surface flux densities*

UV vs Ca II flux densities

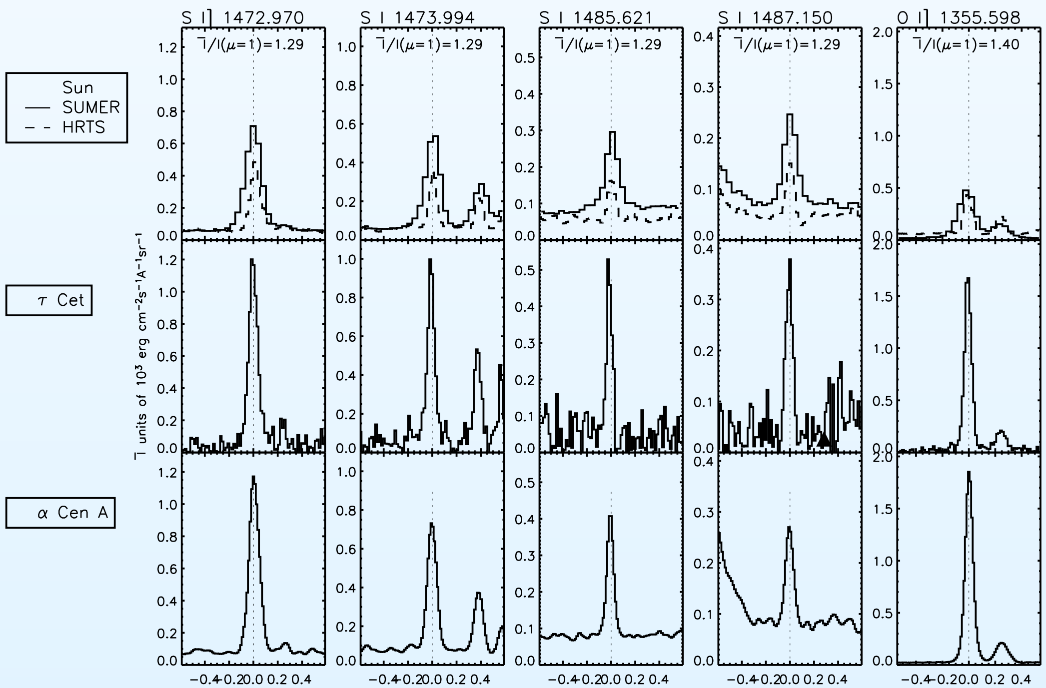


As earlier figure, but abscissae show Ca II surface flux densities

Medium dispersion STIS spectra of τ Ceti and the Sun

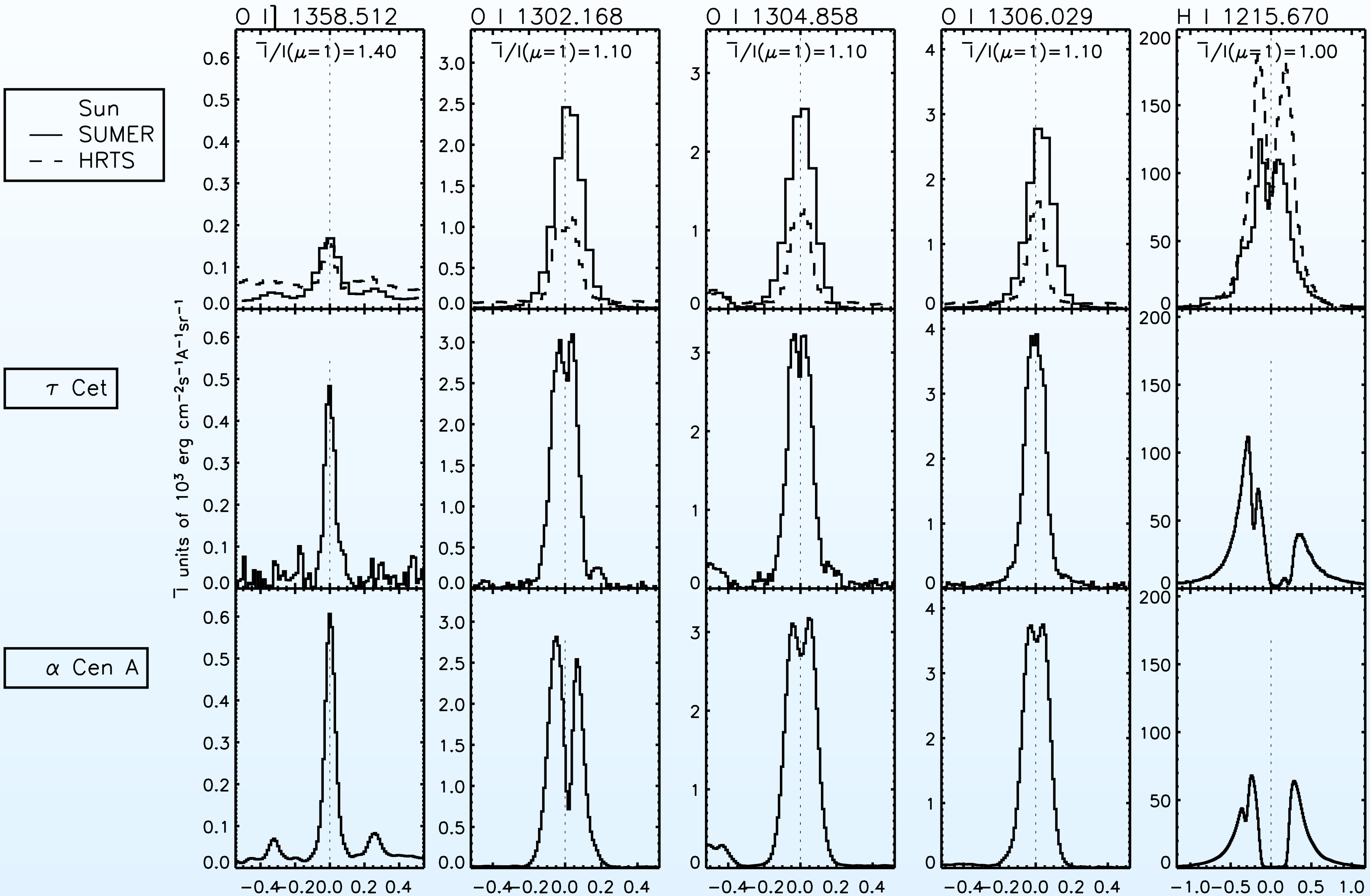
STIS data of α Cen A and HRTS and SUMER data of the quiet Sun (Judge et al. 2004)

- Careful treatment of center-to-limb effects
- solar data represent the disk at cycle minimum with no active network or plage etc.

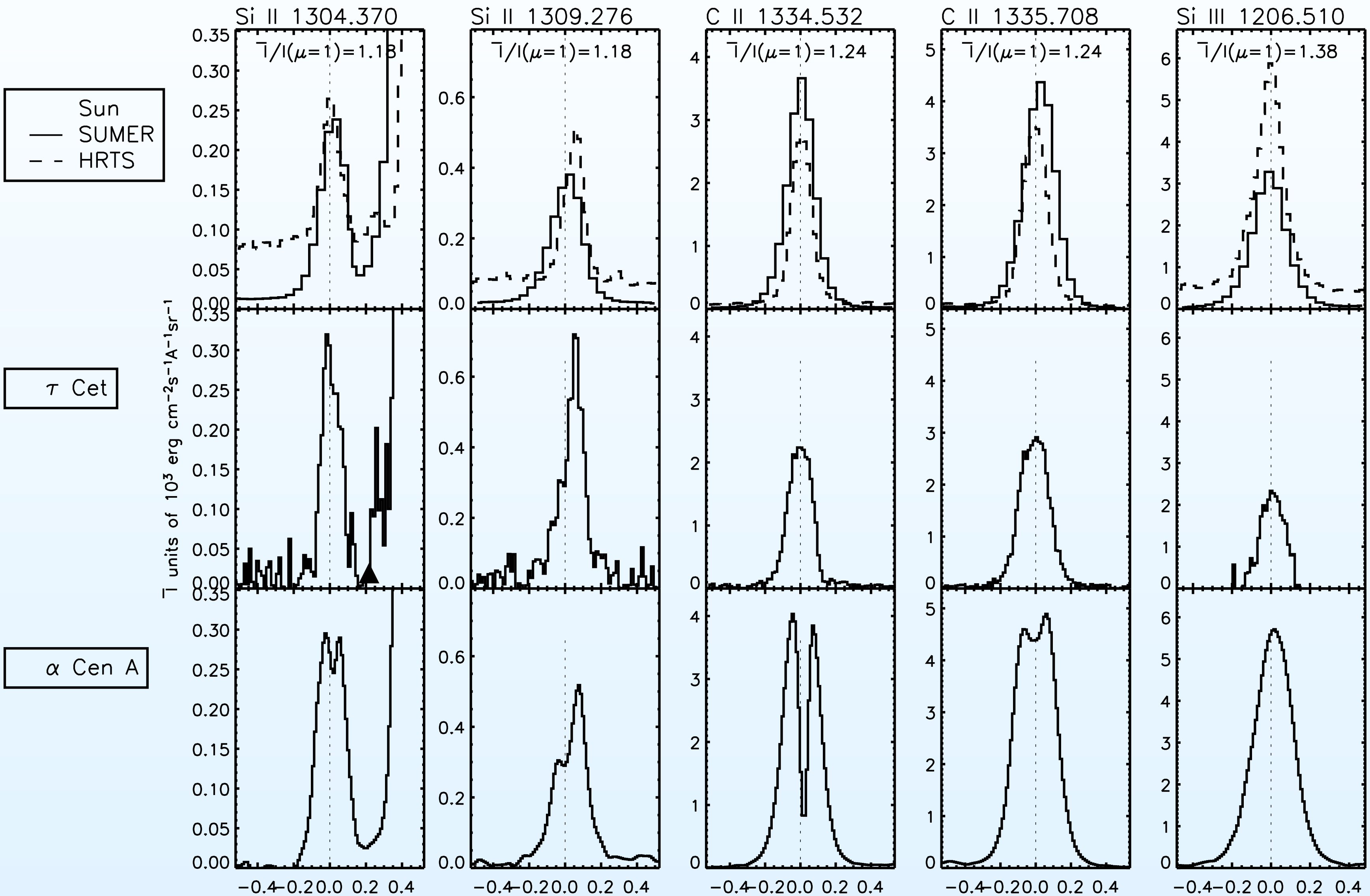


- an example

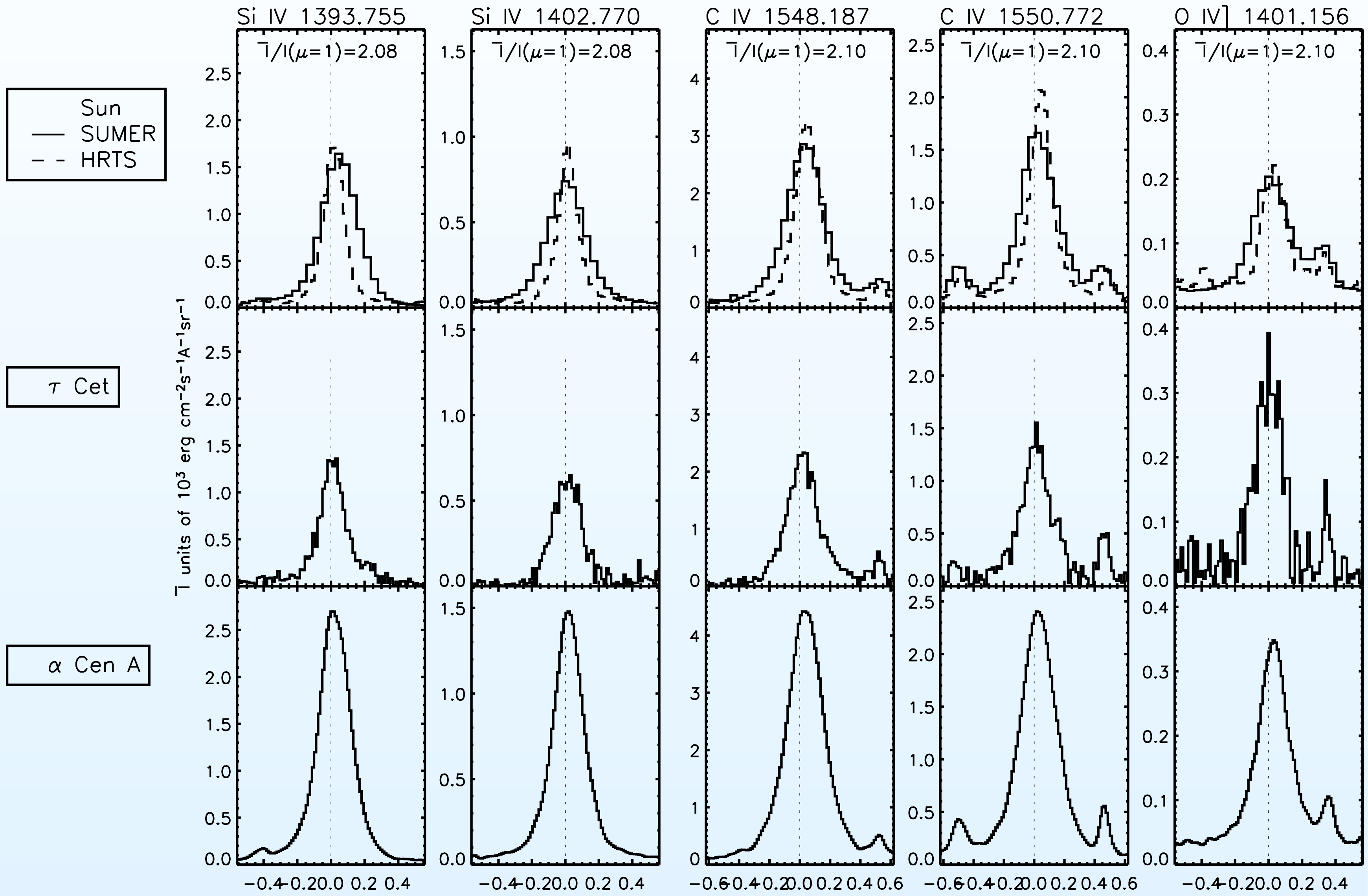
UV spectra of the QS vs α Cen A vs τ Ceti



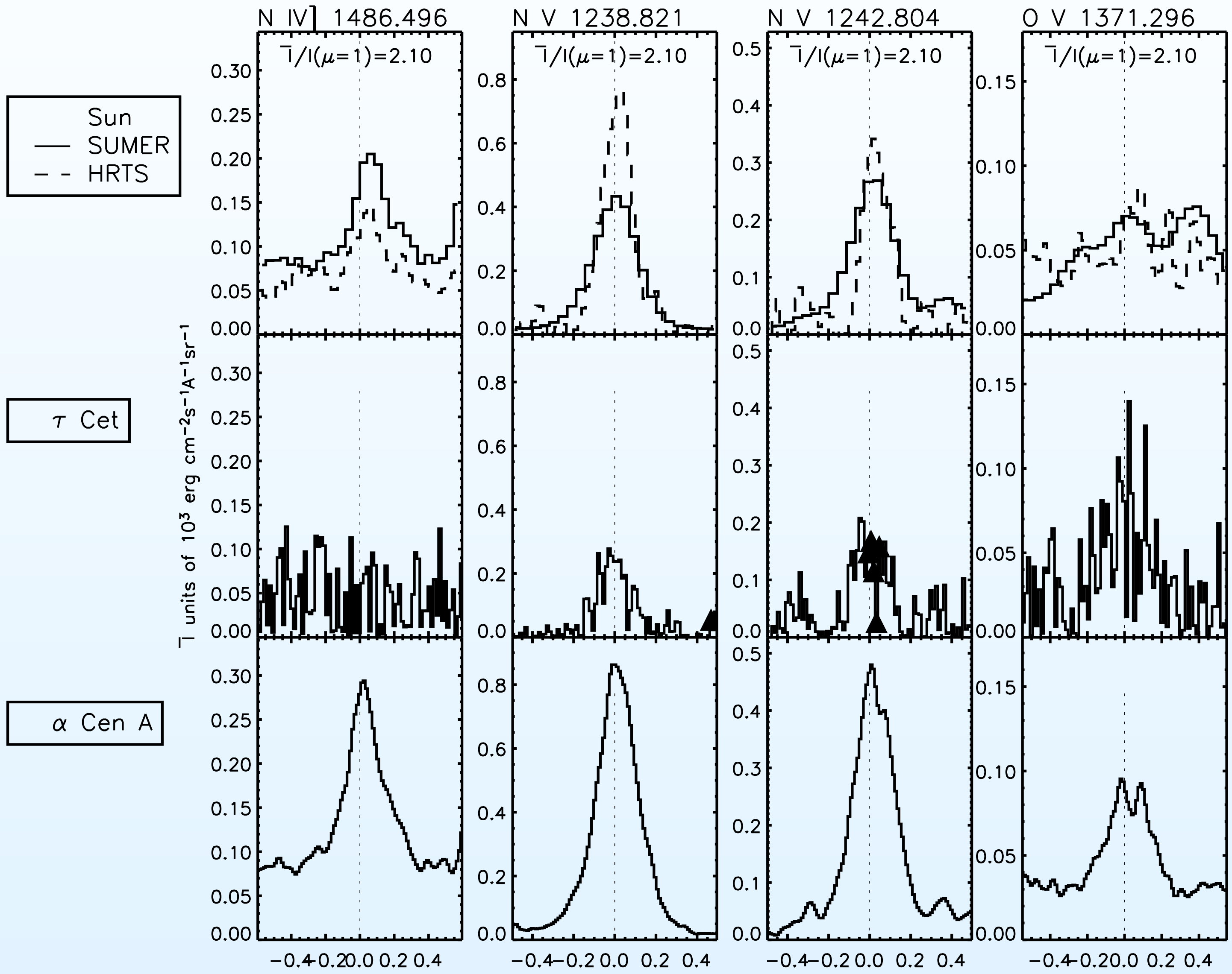
UV spectra of the QS vs α Cen A vs τ Ceti



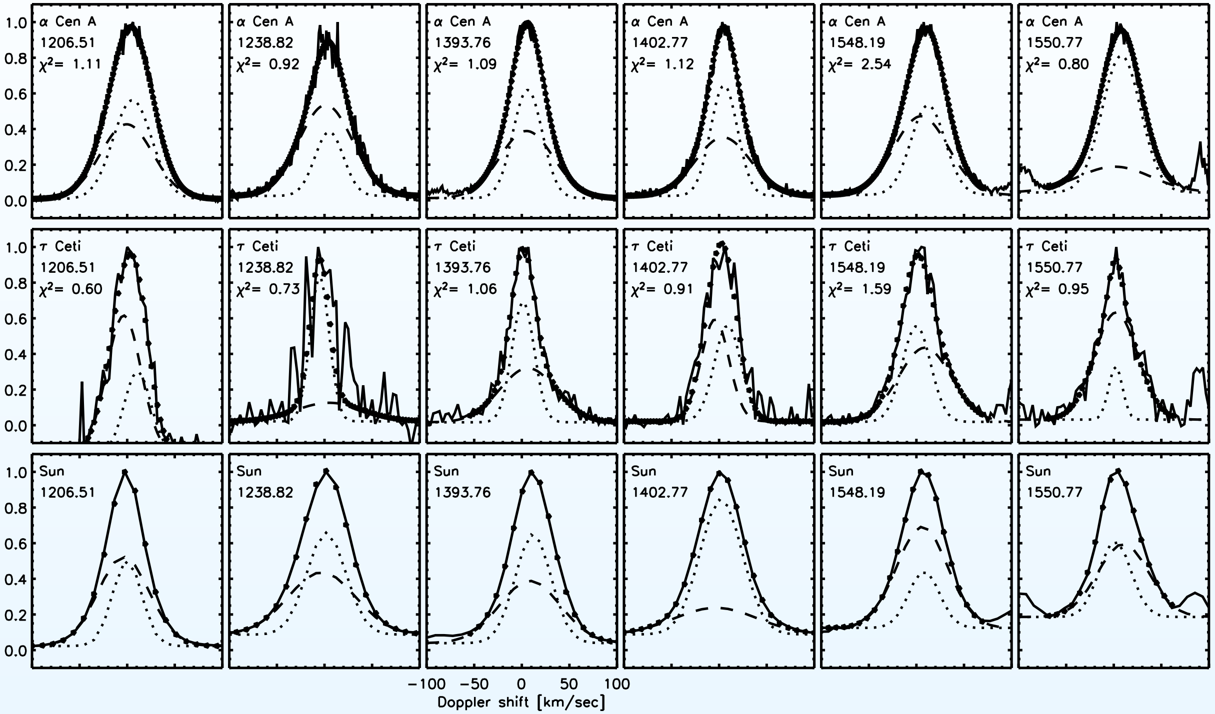
UV spectra of the QS vs α Cen A vs τ Ceti



UV spectra of the QS vs α Cen A vs τ Ceti

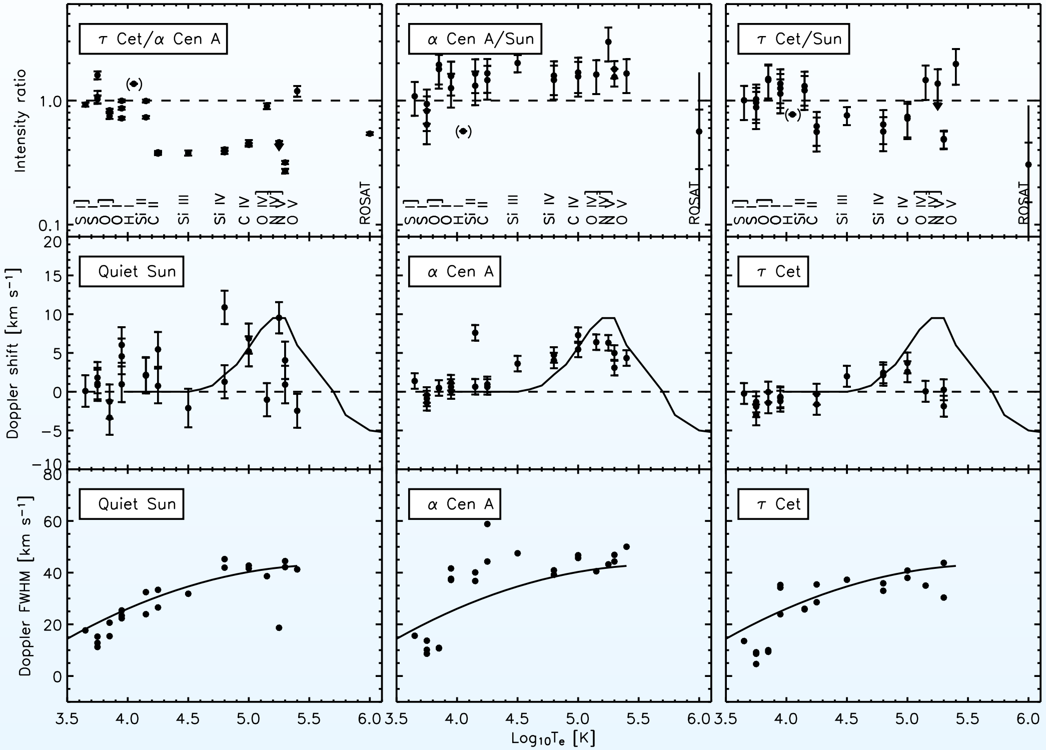


Double Gaussian fi ts



Double Gaussian fits, driven by Genetic algorithm (global minima).
“Consistent behavior” (line ratios). Significant improvement over single Gaussian reduction is seen in reduced χ^2 for the two strongest lines (from 1.8 to 1.1, 1.9 to 1.6).

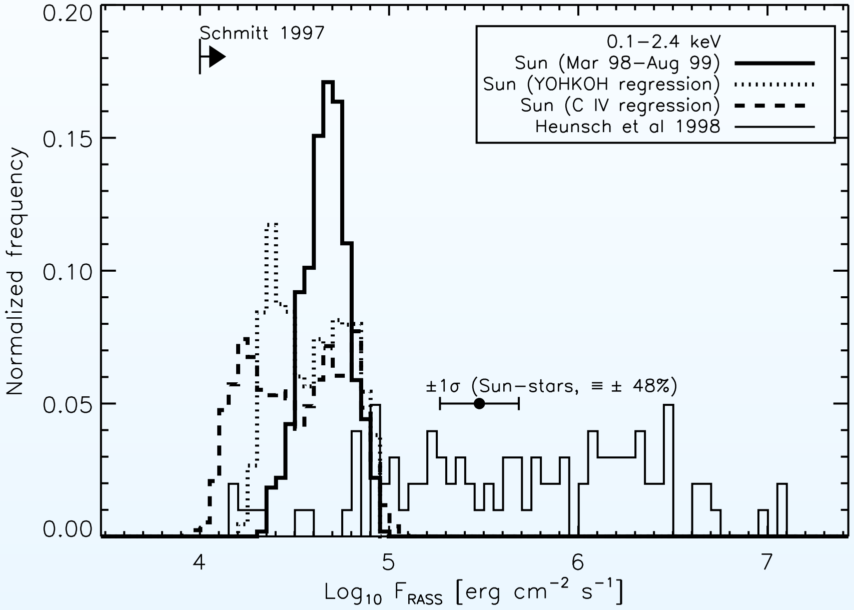
τ Ceti vs. solar line profile properties



- the τ Ceti lower chromosphere $\approx$ solar chromosphere at cycle minimum
- higher regions are weaker, yet still cannot be heated by acoustic waves (cf. Athay & White 1978)
- transition region lines show broad components, but no redshifts –unique

Solar vs. Stellar soft X-ray emission

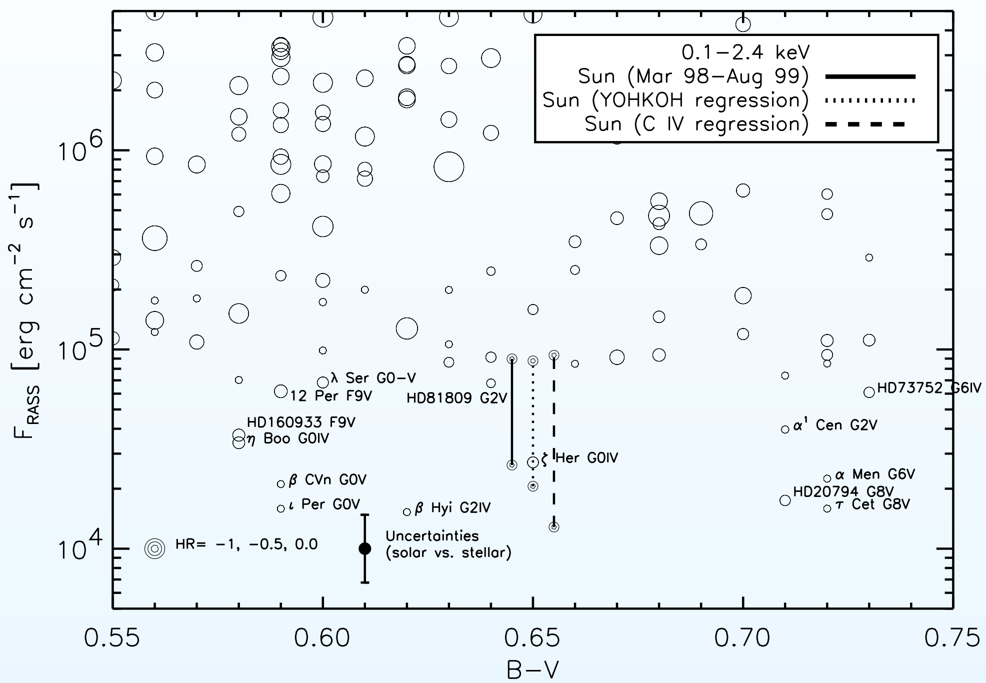
New ROSAT vs. SNOE cross-calibration (Judge et al. 2003)



"The Sun as seen by ROSAT":

At cycle minimum, the solar corona $\approx$ the minimum observed stellar flux density of 10^4 erg cm^{-2} s^{-1}

Solar soft X-ray emission



- Additional uncertainties in the behavior over a complete solar cycle exist because SNOE (operational from 11 Mar 1998) missed the last minimum ($\approx$ January 1997). Nevertheless,
- Predicted solar minimum flux density $\approx$ that of τ Ceti

Summary of Results

Hall & Lockwood (2004): flat activity stars have S index distribution similar to cycling stars, τ Ceti is typical. We find

- τ Ceti has the lowest UV surface fluxes (not lowest S index or Ca II surface flux) of our very inactive "flat activity" stellar sample
- As expected, the S index is a misleading magnetic indicator for the weakly active stars studied here: low S does NOT mean low UV surface fluxes
- τ Ceti has broad components of transition region emission pointing to magnetic activity
- τ Ceti also has the lowest X-ray surface flux density, but requires magnetic activity (Stepien & Ulmschneider 1989)
- Inverse Rossby numbers of τ Ceti (0.47) and the Sun (0.48) are almost identical, suggesting the former is in a Grand Minimum
- It may therefore represent the lowest activity level to which a

Conclusions

- Few (if any) solar-like stars exist with lower chromospheric and coronal surface flux densities than τ Ceti
- Adopting τ Ceti as the lowest activity level reached by the Sun during the Maunder Minimum, we conclude
  - The Sun maintained a magnetic field throughout the Maunder Minimum sufficient to sustain the chromospheric network, the minimum observed coronal flux density with ROSAT, and broad transition region lines associated with the network
  - The lower chromospheric emission was similar to current levels of emission at cycle minimum
  - The surface flux densities of upper chromospheric, transition region and coronal features were perhaps just a factor of 1 to 1.5 below conditions of current solar minima.
- *Caveats:* τ Ceti's rotation axis is inclined ($37^\circ < i < 90^\circ$). The star is metal poor (Fe/H=-0.5).

Possible future work

Is it worthwhile developing an instrument for direct observations of stellar magnetic activity cycles using weak but measurable net circular polarization?

Was the magnetic solar corona absent during the Maunder Minimum, as suggested by Eddy (1976)?

- Search further historical records for reports on coronal structure during eclipse, and
- compare with 20th century measurements at cycle sunspot minima.
- Probe coronal emission of “flat stars” with more sensitive instruments (XMM-Newton, Chandra).

contact `judge@ucar.edu`

references

Athay R. G., White O. R., 1978, ApJ 226, 1135

Baliunas S., Jastrow R., 1990, Nat 348, 520

Baliunas S. L., Donahue R. A., Soon W. H., Horne J. H., Frazer J., Woodard-Eklund L., Bradford M., Rao L. M., Wilson O. C., Zhang Q., Bennett W., Briggs J., Carroll S. M., Duncan D. K., Figueroa D., Lanning H. H., Misch T., Mueller J., Noyes R. W., Poppe D., Porter A. C., Robinson C. R., Russell J., Shelton J. C., Soyumer T., Vaughan A. H., Whitney J. H., 1995, ApJ 438, 269

Beer J., 2000, Space Sci. Rev. 94

Eddy J. A., 1976, Science 192, 1189

Hall J. C., Lockwood G. W., 2004, ApJ submitted

Judge P. G., Saar S., Ayres T. R., Carlsson M., 2004, ApJ in press

Judge P. G., Solomon S., Ayres T. R., 2003, ApJ 593, 534

Saar S. H., 1998, in R. Donahue, J. Bookbinder (eds.), ASP Conf. Ser. 154: Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, 211

Stepien K., Ulmschneider P., 1989, A&A 216, 139

White O. R., Skumanich A., Lean J., Livingston W. C., Keil S. L., 1992, PASP 104, 1139