Precise Calcium Abundance Determinations for 207 Flare Decays observed by the BCS Channel 1 aboard SMM

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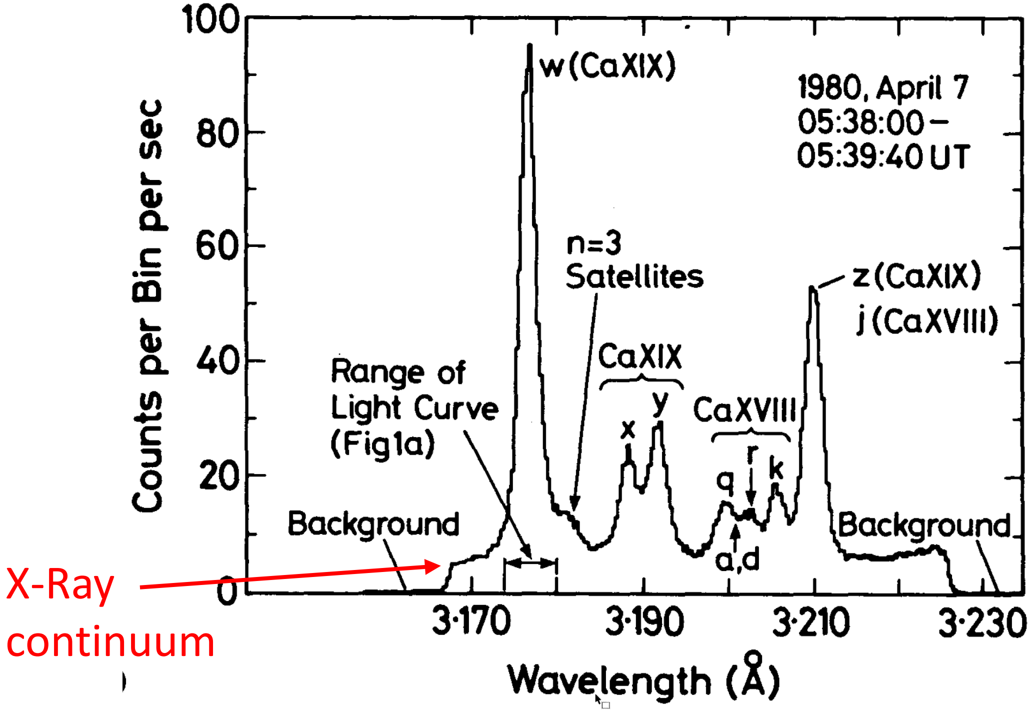
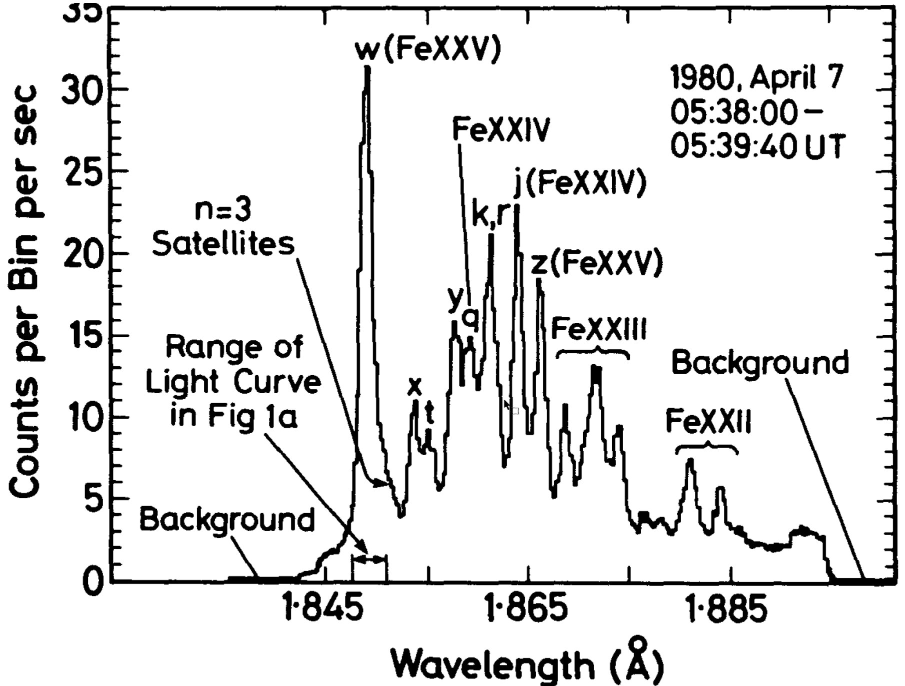




The SMM high-resolution spectra of Ca XVII-XIX & Fe XX-XXVI ions are still the best in astrophysics...

continuum is observed (free from crystal fluorescence) and high spectral resolution.

<u>However, early analyses assumed:</u>

- Ideal cylindrical geometry of Bragg crystal surface, so a linear dependence of

  bins → λ's and

Linear transformation of observed (counts/bin) to reduced line intensities (photons/Å)

- No electronic ageing effects
- Continuum levels fitted as a parameter in the gaussian fitting to the resonance Ca XIX w line
- Thus (only) line intensities were used to find observed line/continuum ratios → A_{Ca}.

Culhane et al..

The Astrophysical Journal, 244:L141–L145, 1981 March 15

Findings of earlier analyses [Nature (1984) and ApJ (1998)] of line-to-continuum ratios

Nature, Vol. 310, No. 5979, pp. 665-666, 23 August 1984

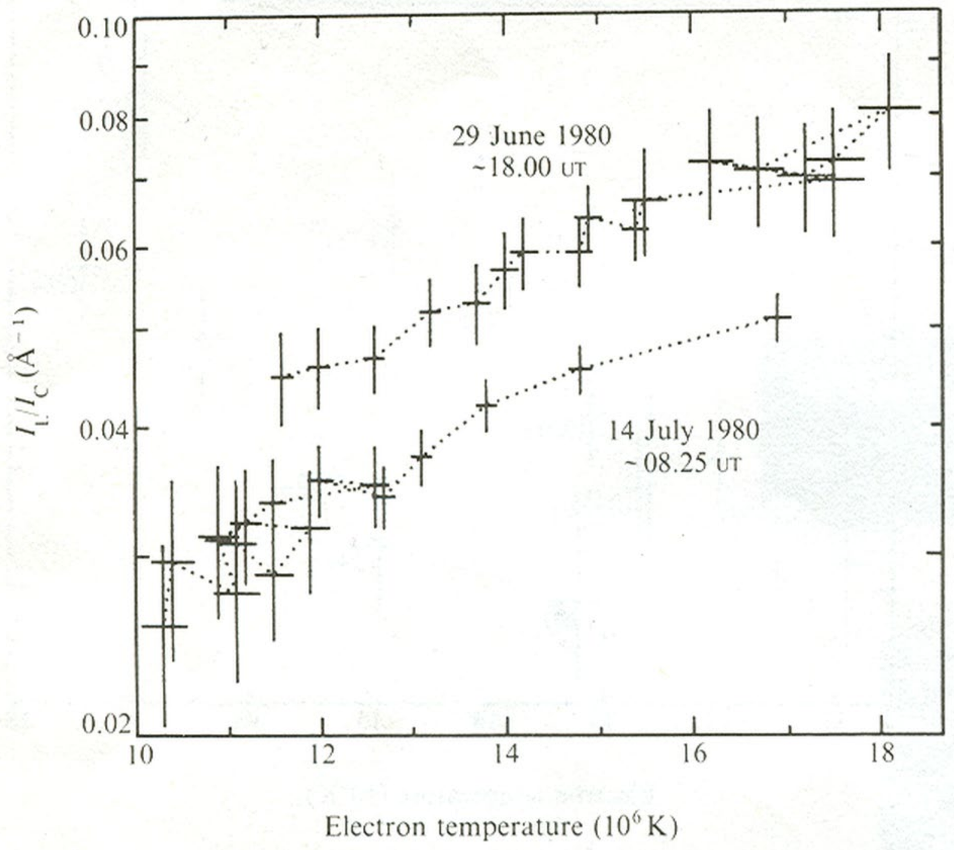


Fig. 2 I_L/I_C for cooling phases of two different flares. The error bars are as in Fig. 1. The constant vertical shift corresponds to a variation in the calcium abundance by a factor of 1.4.

- Systematic changes of L/c (line/continuum) ratio between flares
- These changes interpreted as evidence for changing A_{Ca} between flares since:

I_L ~ abundance of Ca ions (A_{Ca})

I_c ~ proton density (Bremsstrahlung)

- Absolute values of A_{Ca} were determined for 100+ flares observed during decay phases

THE ASTROPHYSICAL JOURNAL, 501:397–407, 1998 July 1

Reasons for new analysis to get flare Ca abundance

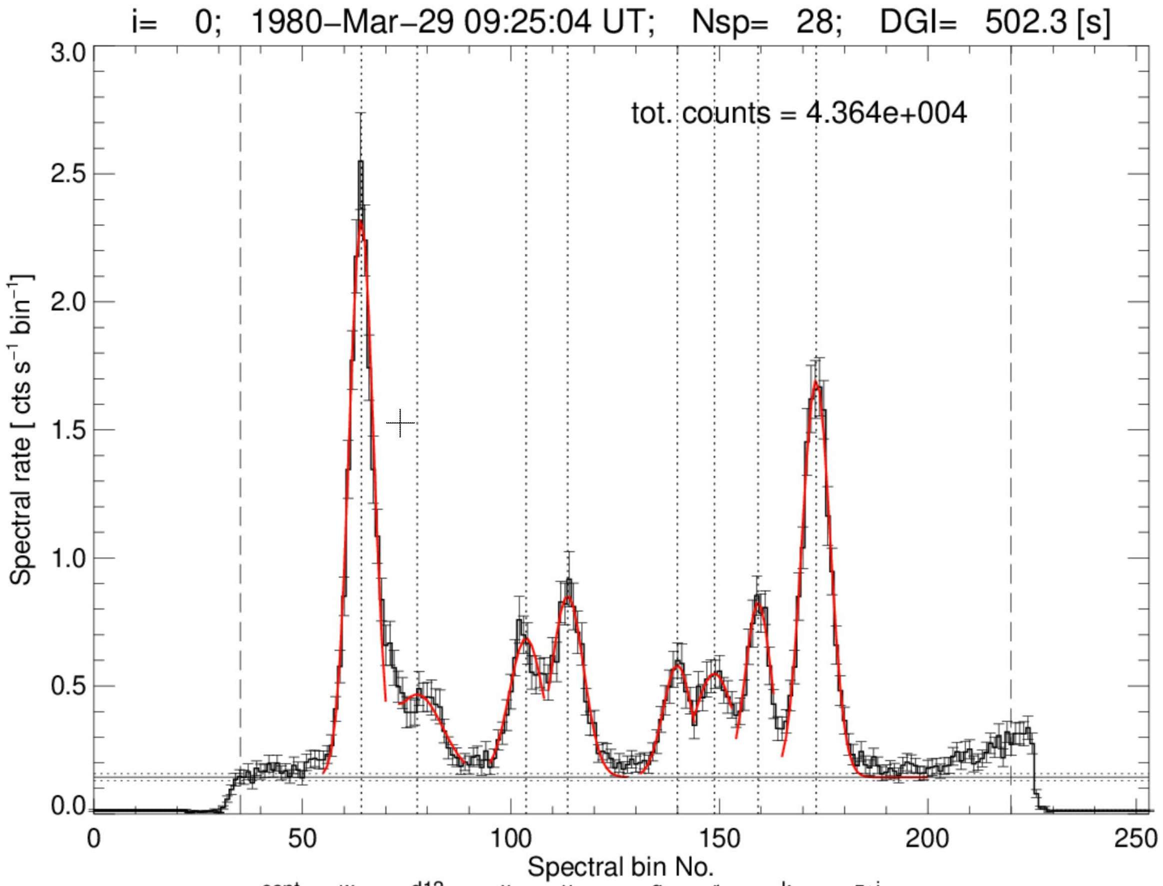
New Results from the *Solar Maximum Mission/Bent Crystal Spectrometer*

Solar Phys (2017) 292:50
DOI 10.1007/s11207-017-1070-y

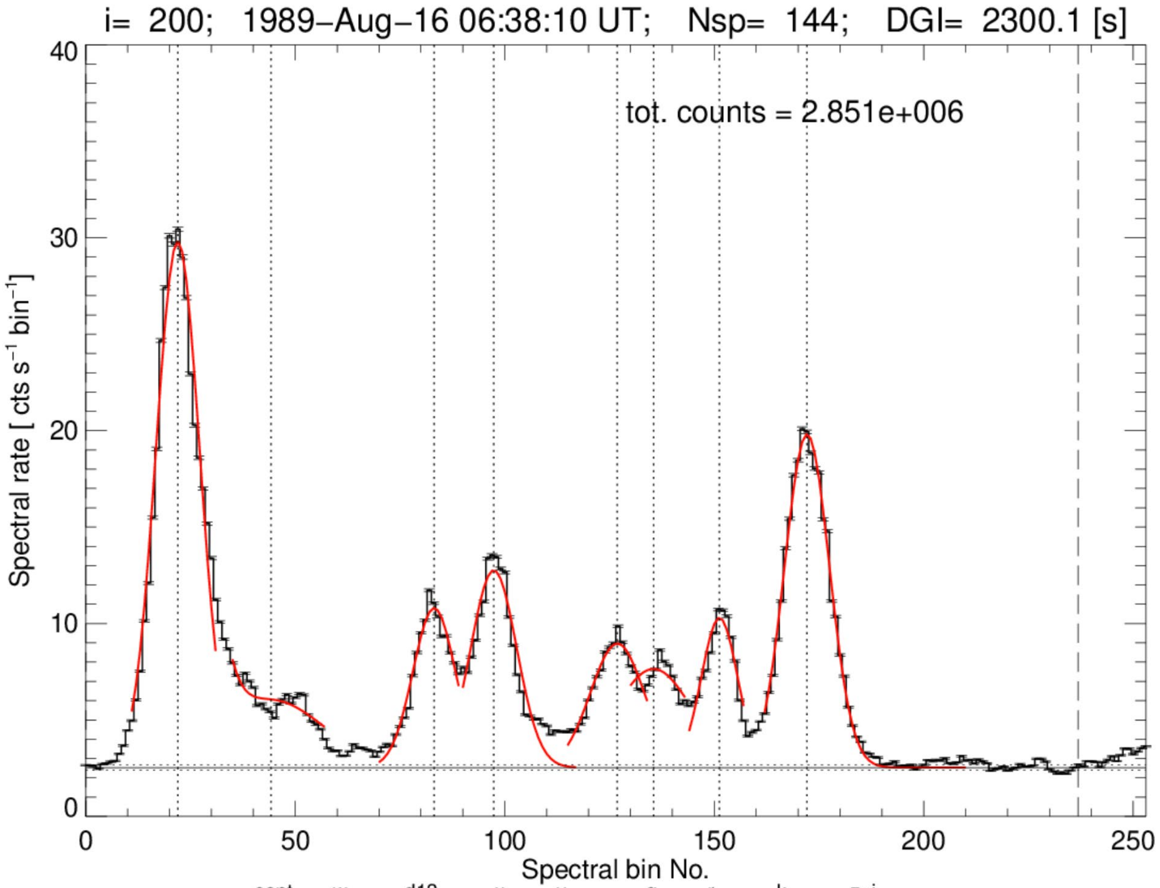
C.G. Rapley[1] · J. Sylwester[2] · K.J.H. Phillips[3]

- **A new analysis of SMM BCS instrument parameters** (Rapley et al. 2017):
  - Taking account of crystal non-uniformities
  - Corrections for detector saturation
  - Determination of flare source within the BCS collimator FOV
  - New calibration to get BCS spectra in spectral irradiance units
- **Inclusion of updated atomic theory**:
  - Continuum fluxes based mostly on CHIANTI
  - Line spectra with additional satellite line calculations from Cowan atomic code
- **From this, using BCS channel 1 spectra, we confirm earlier studies showing flare-to-flare variability of absolute calcium abundance in flaring plasmas**

Example observed spectra with gaussian fits to principal lines

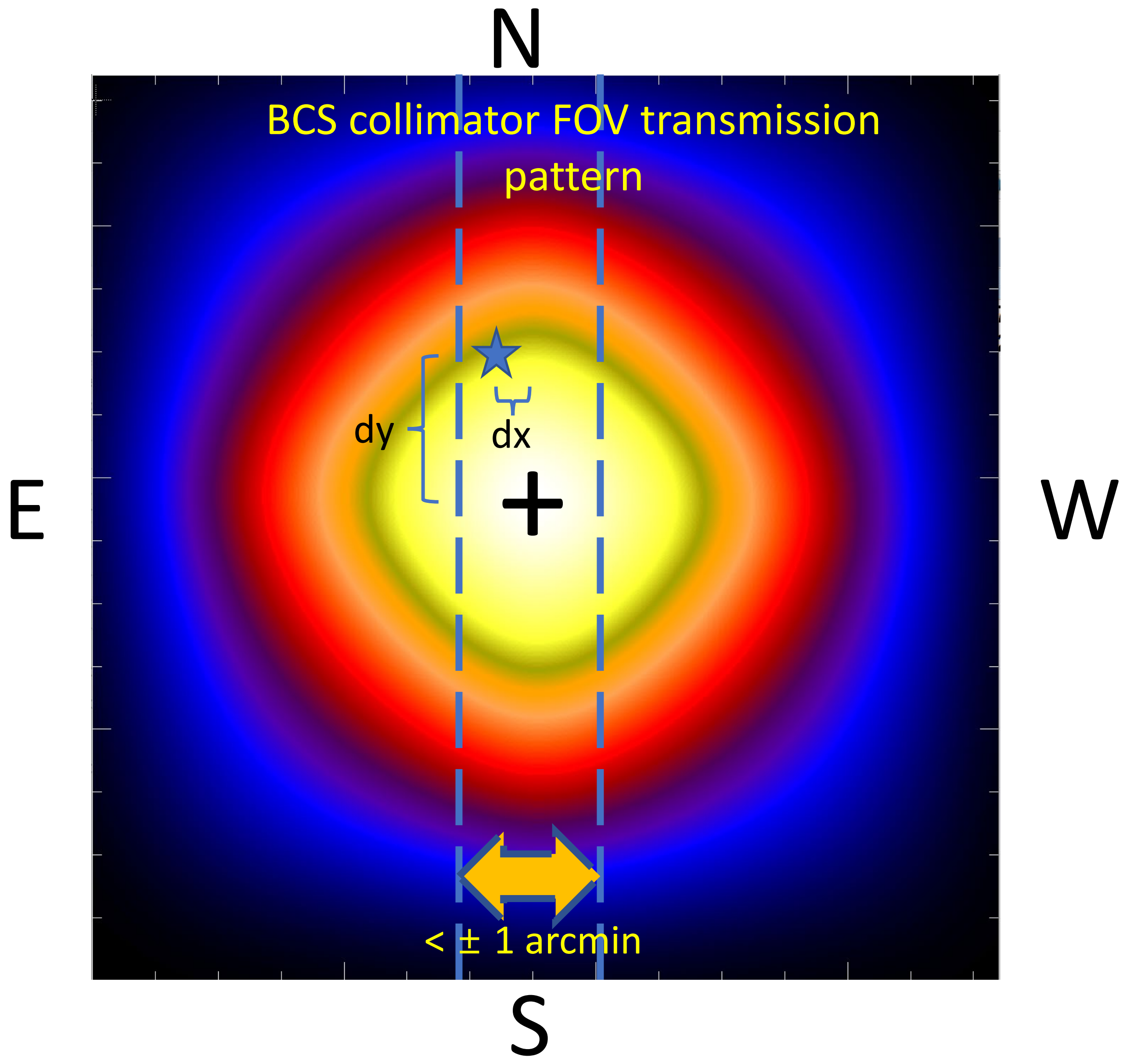


	cont.	w	d13	x	y	q	r	k	z+j	
	0.144	64.24	77.56	103.67	113.63	139.92	148.78	159.30	173.19	[bin]
±	0.014	0.22	0.61	0.30	0.17	0.12	0.27	0.17	0.06	[bin]



	cont.	w	d13	x	y	q	r	k	z+j	
	2.530	22.05	44.23	83.16	113.63	126.86	135.51	151.25	172.14	[bin]
±	0.131	0.37	1.09	0.18	0.33	0.23	0.97	0.23	0.06	[bin]

Flare Selection for the new analysis



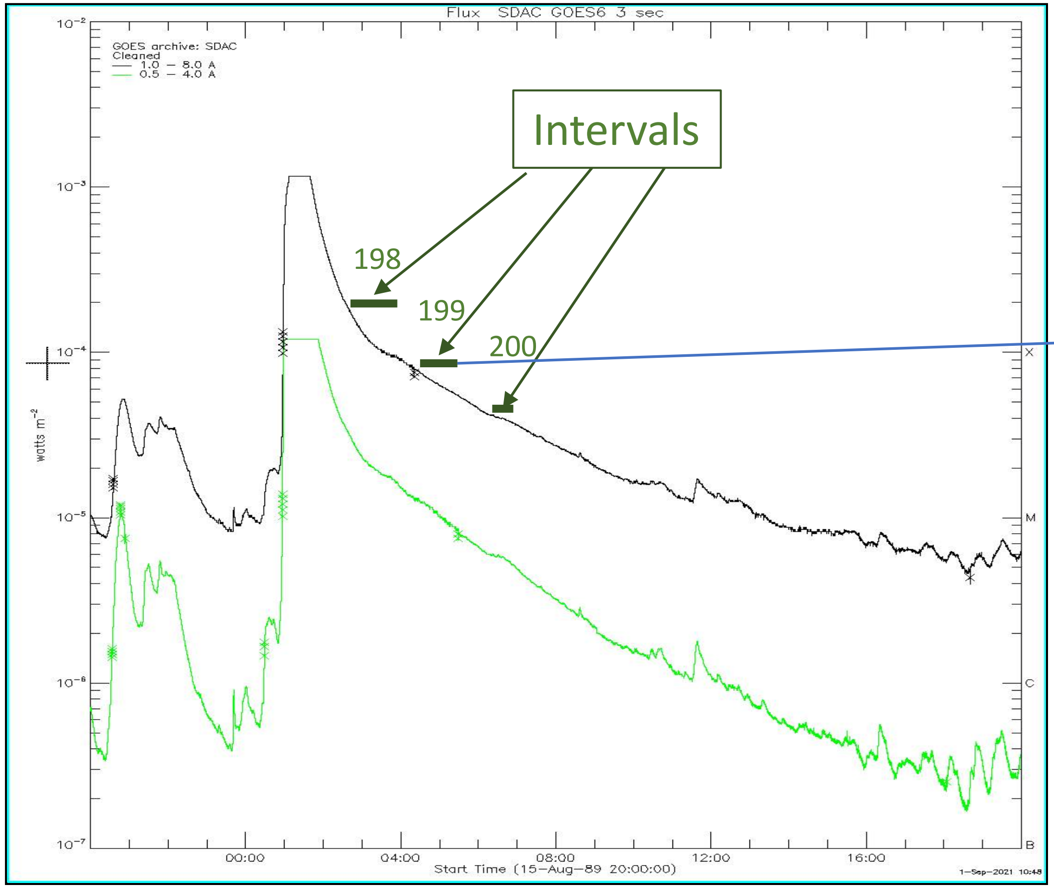
- Flares chosen from the (nearly) complete NASA/GSFC SMM archive
- Flares with positions near the BCS collimator boresight (along dispersion E-W direction: dx)
  - Offsets of line positions (corresponding to dx) had to be small, within ± 2 spectral bins from the home positions
  - This minimises crystal curvature effects
- Decay phase spectra only chosen:
  - Small effects of turbulent broadening or blueshifts
  - Isothermal assumption valid

Use also made of GOES X-ray monitoring in two channels: 0.5 – 4 Å (G_H) and 1 - 8 Å (G_L)

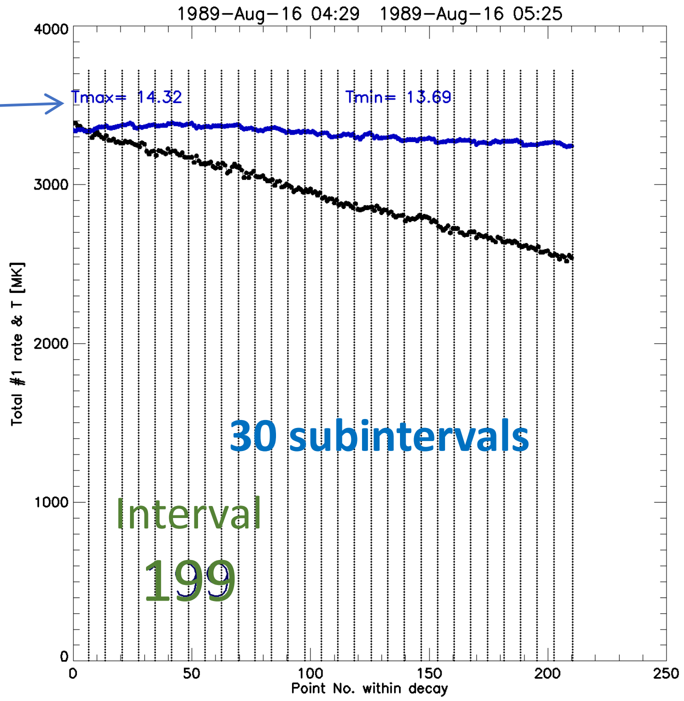
- GOES-2, -5 & -6 monitored total solar X-ray fluence every 3s in the bands:
  - 0.5 – 4 Å (G_H) → 3.1 – 24.8 keV
  - 1 - 8 Å (G_L) → 1.55 – 12.4 keV
- Assuming isothermality, temperature T_G was obtained from the flux ratio (G_H)/ (G_L) (*goes* SSW package, every 3s)
- Emission measure EM_G (from G_L & T_G)
- To avoid the contribution of non-flaring ARs to G_H & G_L fluxes, the pre-(post-) flare levels (b_H & b_L) were subtracted from G_H & G_L giving better estimates (T_{Gb} & EM_{Gb}) corresponding to flaring source seen through the BCS collimator [note: GOES is a full-Sun instrument]
- Unfortunately:
  - there are gaps in GOES coverage for some BCS flares;
  - sometimes estimates of b_H & b_L levels were uncertain leading to higher uncertainties in the derived T_{Gb} & EM_{Gb} values.

GOES light curves were used to select suitable BCS flare decays

GOES light curves for X17 class flare on 16 August 1989



AR 5629 S18W84

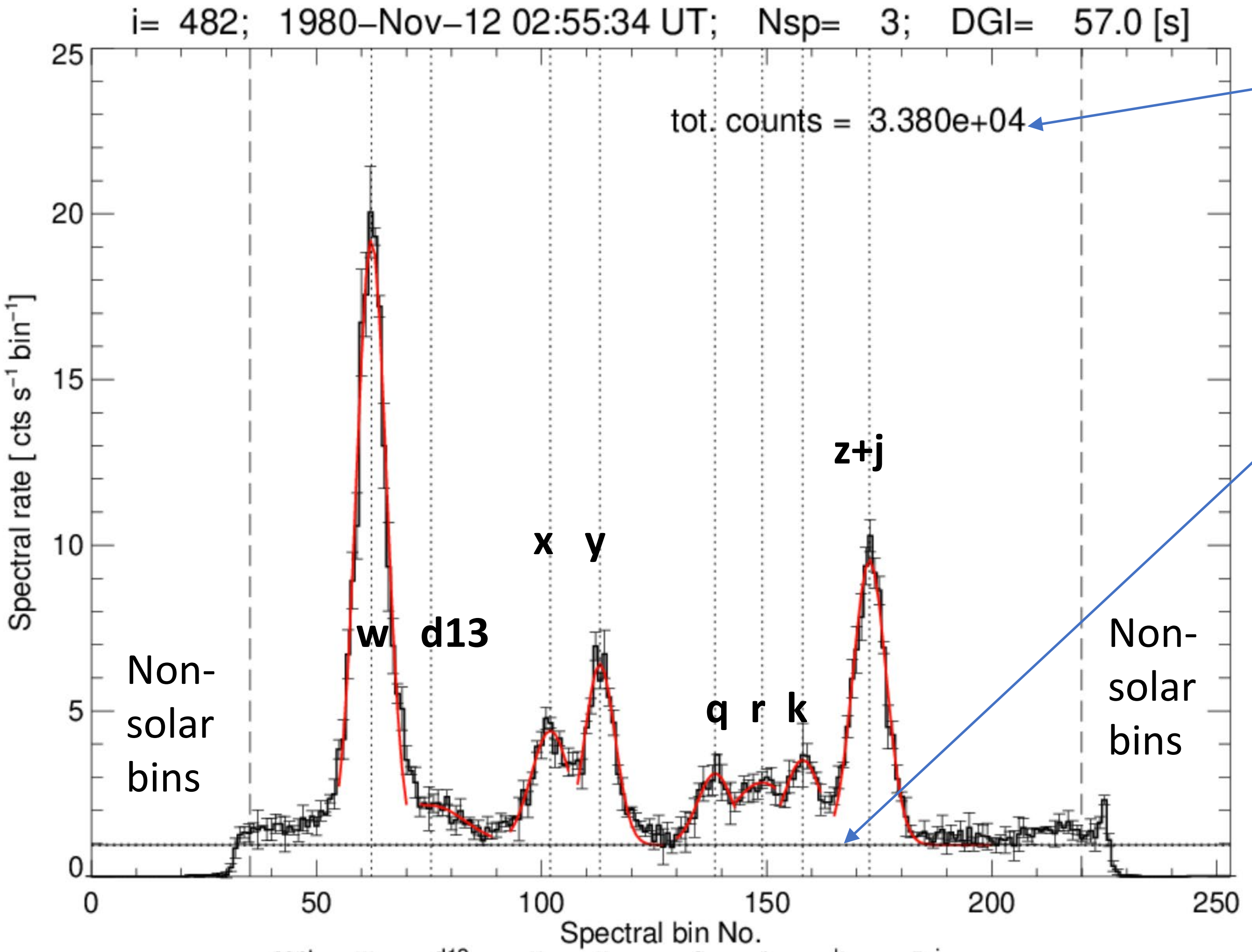


- 207 decay intervals were selected for ~194 flares
- Each interval was divided into several sub-intervals for which:

  T_G - the temperature derived from flux ratios, and also the corresponding **EM_G -the emission measure** both of which did not change significantly and were a good characterization of the average temperature of the hotter flaring plasma component.

Overall 2806 subintervals analysed

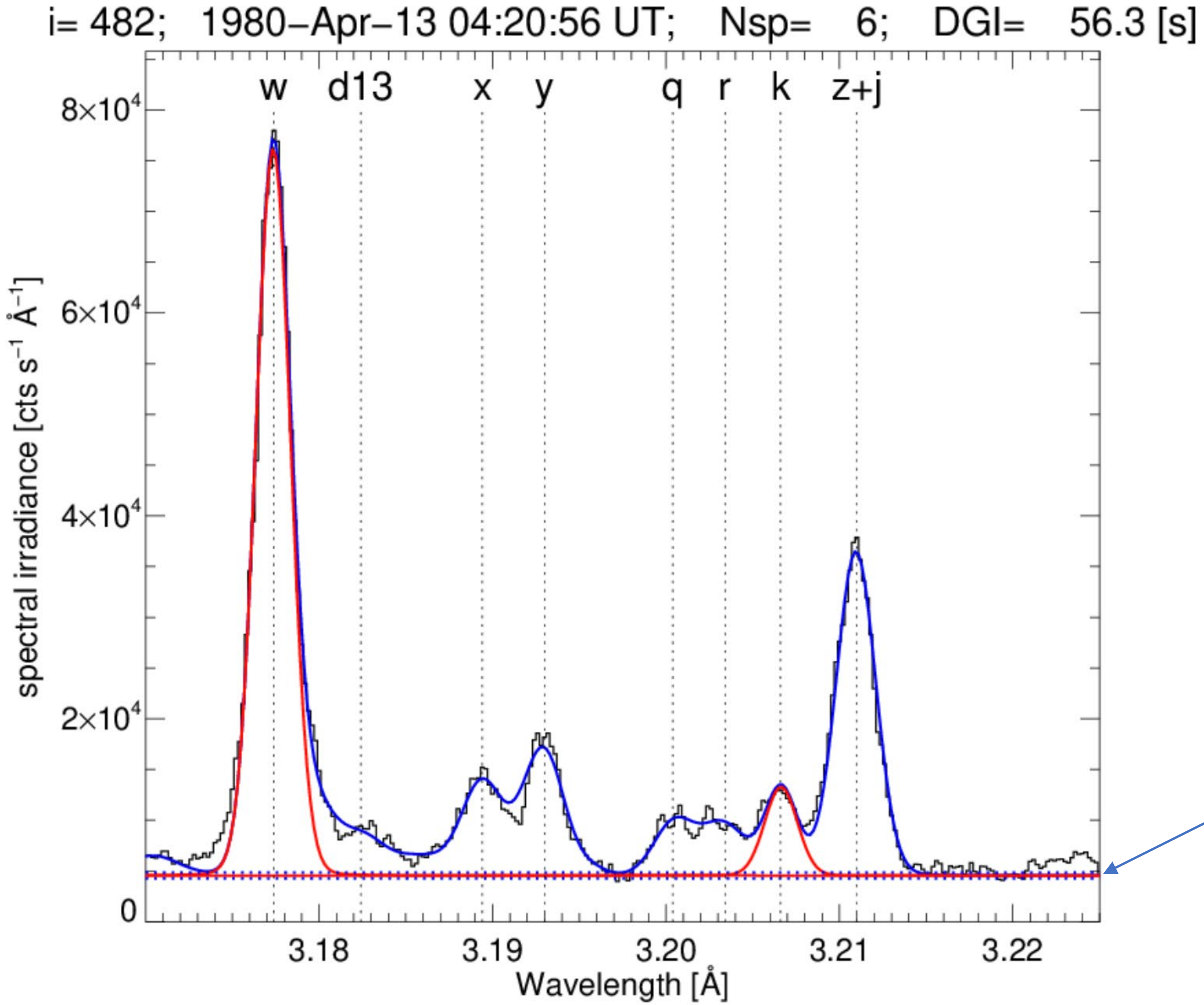
Averaged spectra for subintervals (i) were fitted with gaussians to 8 principal lines: bins → λ's



	cont.	w	d13	x	y	q	r	k	z+j	
	0.957	62.27	75.42	101.95	113.95	138.56	148.99	158.02	172.85	[bin]
±	0.032	0.13	1.78	0.31	0.18	0.30	0.87	0.26	0.09	[bin]

- Large count rates were collected even for low-X-ray class events
- First, the continuum taken as an average of few lowest bins in the true spectral range (between dashed lines) were estimated with uncertainties
- Next 8 individual gaussians were fitted to the lines on top of the continuum
- Precise line centre bins allowed to assign smoothly wavelengths to bins (nonlinear dependence specific to every subinterval) taking thus into account crystal deformations and detector's electronics effects (ageing).

Example reduced Ca XVIII-XIX spectrum with multi-component Voigt fit



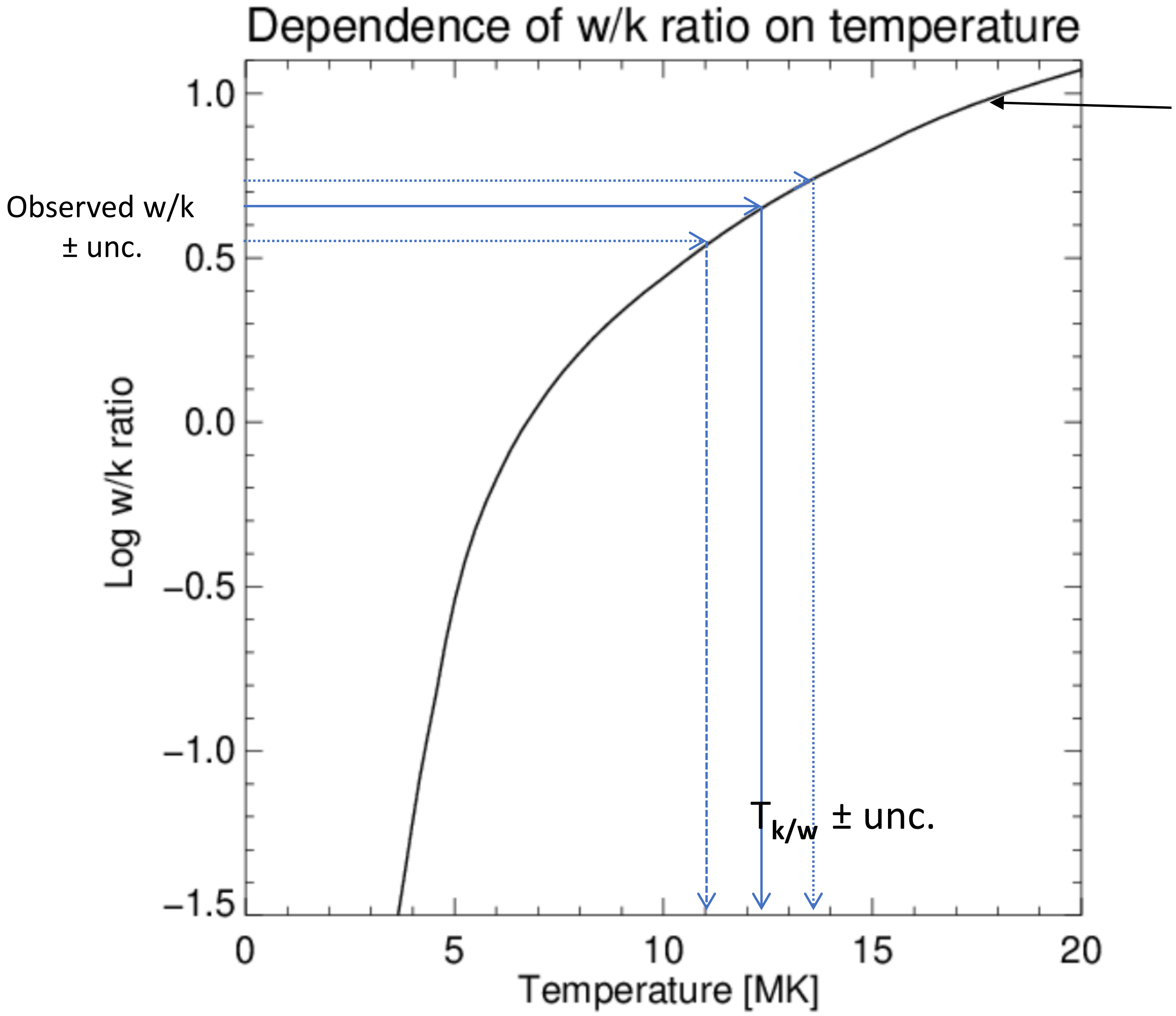
The reduction:

- Bins were converted to wavelengths (spectral bins every 0.0002 Å) in non-linear way using smooth min_curve_surf 5**th** order polynomials
- Intensities [cts/bin/s] expressed in [cts/s/Å] taking into account local crystal curvature nonlinearities & detector aeging
- Resulting spectral irradiances were fitted with 13 line-component Voigt profiles (including 8 primary lines indicated)
- the continuum (±unc.) was re-fitted based on 20 lowest intensity spectral bins

Quantities derived & used in the following analysis:

- For 2806 subintervals
  - Continuum levels with uncertainties [cts/s/Å]
  - Fluxes in 8 main lines (+ 5 other necessary for the good fit) with uncertainties
  - Total flux in lines F_T above the continuum within the range from 3.167 to 3.227 Å
- For 2718 subintervals for which corresponding GOES data were available
  - T_{Gb} - the temperature (average over subinterval) with uncertainties (after pre-flare background removal)
  - EM_{Gb} - the emission measure (average over subinterval) with uncertainties
  - Times of "parent" flare maximum defined
  - X-ray source placement (positions **dx** and **dy)** within the FOV of BCS collimator
- In addition, from old solar activity catalogues:
  - the flare-associated active region number
  - where available H**α** importance was assigned (not usually available for limb flares)
  - (Parent flare) location on the disc

The interpretation (atomic theory, Cowan code, CHIANTI)



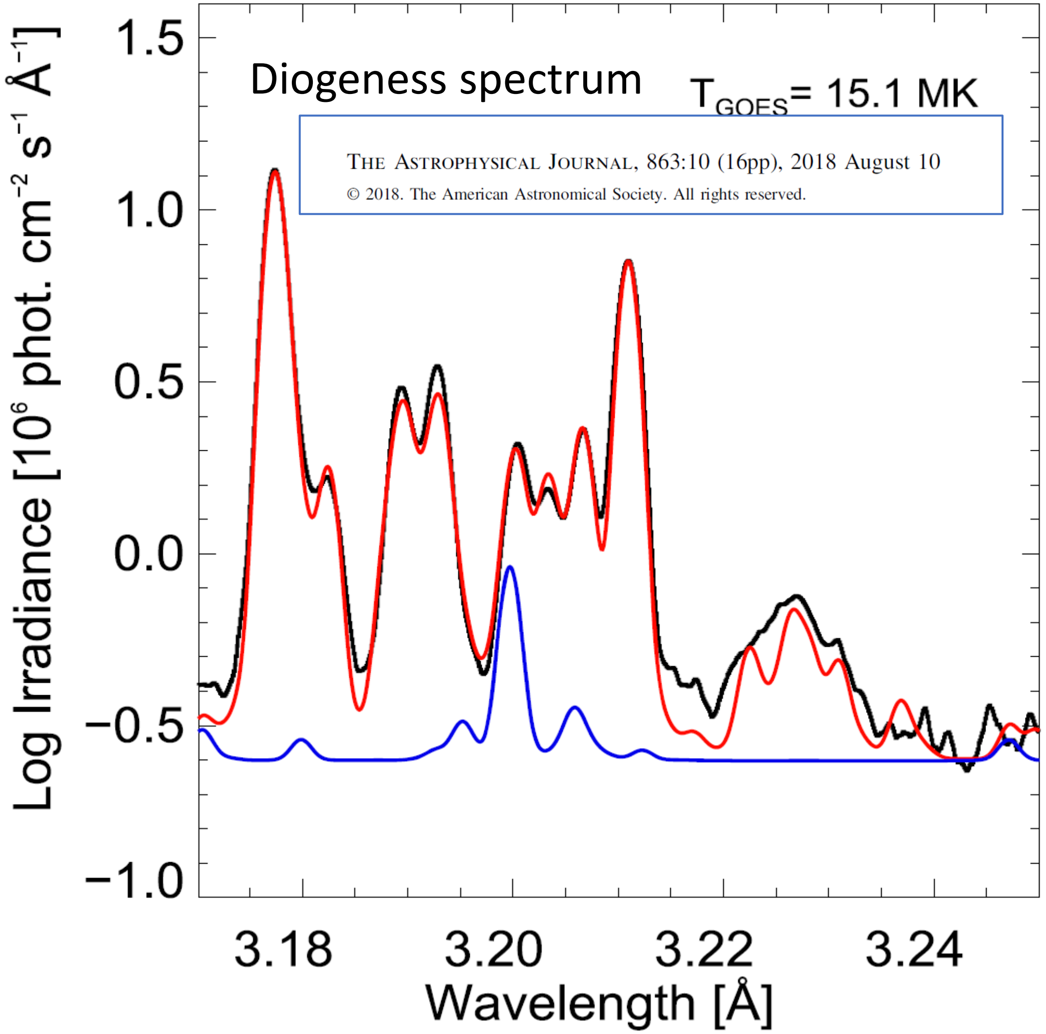
Calibration curve was determined from 13- line multi-Voigt fit to synthetic spectra calculated for isothermal plasma at changing temperaturę T.

Allowance was made for small (~3%) contribution of several Ar XVII and Ar XVIII ion lines falling in the spectral range of BCS.

From 2806 observed spectra, the k & w line intensities were determined and their ratios used to find temperature $T_{k/w}$ together with uncertainties

There are Ar lines blending with the Ca spectrum but their total contribution is tiny & well known

K. J. H. Phillips[1], J. Sylwester[2], B. Sylwester[2], M. Kowaliński[2], M. Siarkowski[2], W. Trzebiński[2], S. Płocieniak[2], and Z Kordylewski[2]



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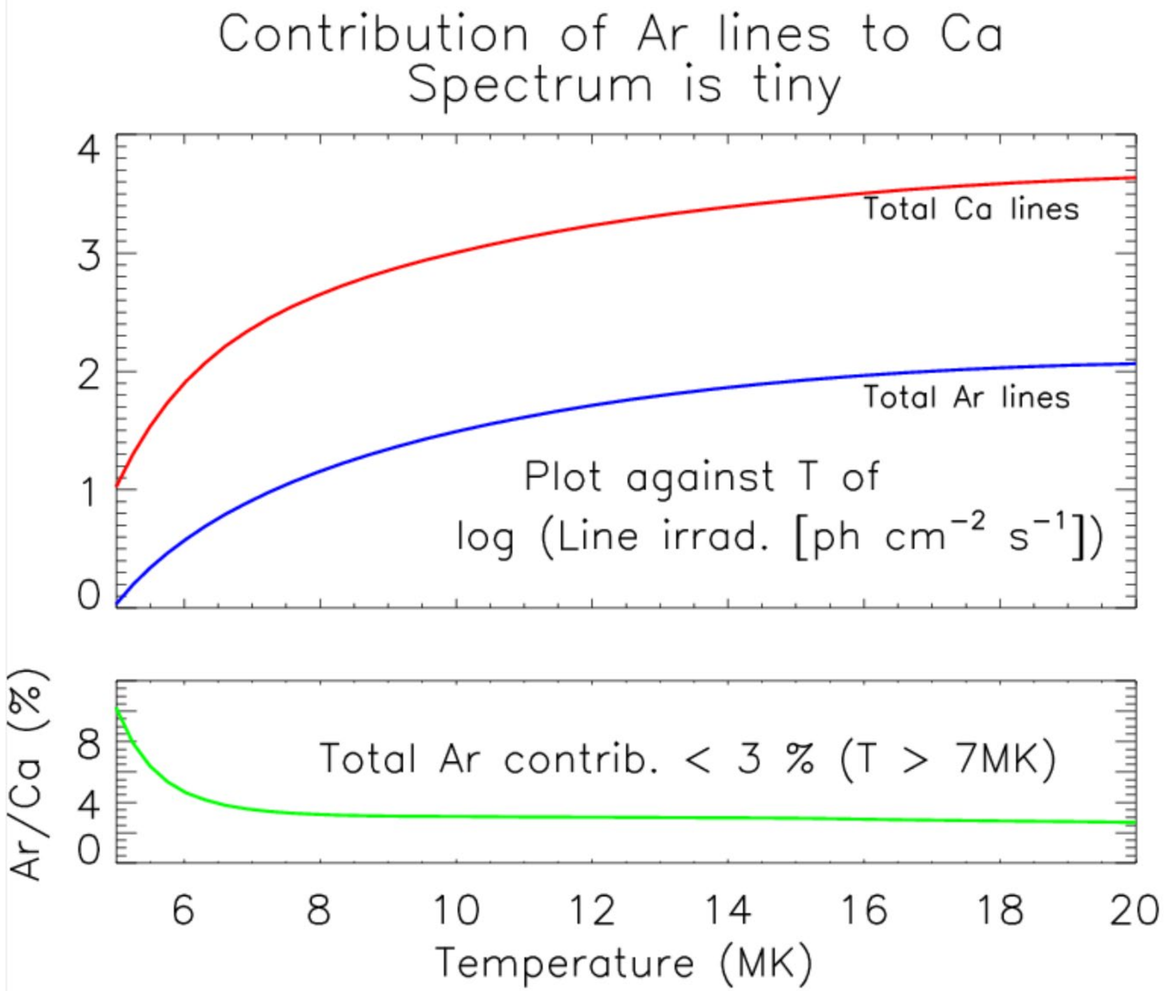


Differences/improvements between previous and present analyses

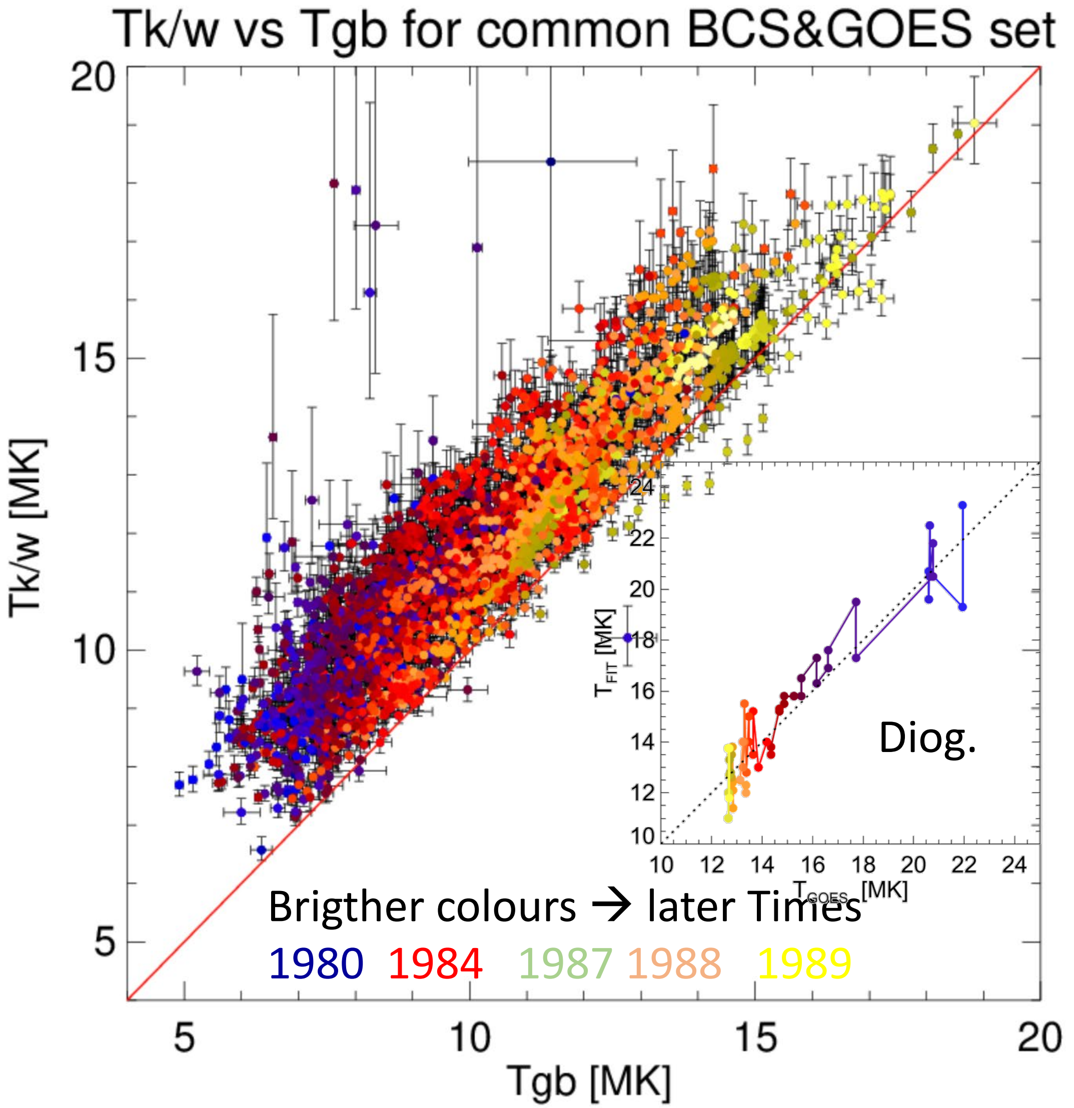
Old approach: ApJ 501, 397 1998

- Linear crystal dispersion – crystal nonuniformities neglected
- Gaussian line fits to lines
- Somewhat uncertain continuum levels (resulting from gauss fits)
- Atomic theory as of mid 1980s
  - Continuum T-dependence adjusted semi-empirically (J.R. Lemen)
- Absolute abundances of calcium determined from resonance Ca XIX w (only) line-to-continuum ratios, average values for flares given only
- Significant T-dependence of w/c ratios over flaring temperaturę range inherent

Present analysis (2021)

- Non-linear dispersion adopted accomodating crystal & detector effect → changes in relative line intensities
- Voigt multicomponent line fits used with appropriate handling of crystal rocking curves → better line fits
- New approach used to continuum level determination on the reduced spectra with precisely defined uncertainties
- Approx. 2000 weak satellites added to theory synthetic spectra calculations, higher-***n*** contributions included, Ar line contribution allowed for (as included in CHIANTI)
- Theoretical continuum calculations based on CHIANTI with appropriate allowance for coronal plasma composition
- Absolute abundances determined from total line flux to continuum ratios (F_T/c)
- Weaker dependence of F_T/c on temperature within flaring T-range; much more accurate Aca determinations based on ~twice larger count rates and better defined continuum with narrower uncertainties

Results: relation of T_{Gb} and $T_{k/w}$ for all subintervals



- Temperatures T_{Gb} and $T_{k/w}$ correlate well
- $T_{k/w}$ nearly always >T_{Gb} (OK for multi-T plasma)
- For individual flares the points „goes” parallel to diagonal at the level reflecting proportion of hotter-to-cooler DEM (differential emission measure)
- Confirms results obtained from the study of Ca spectra by Diogeness flat crystal scanning spectrometer (see inset)

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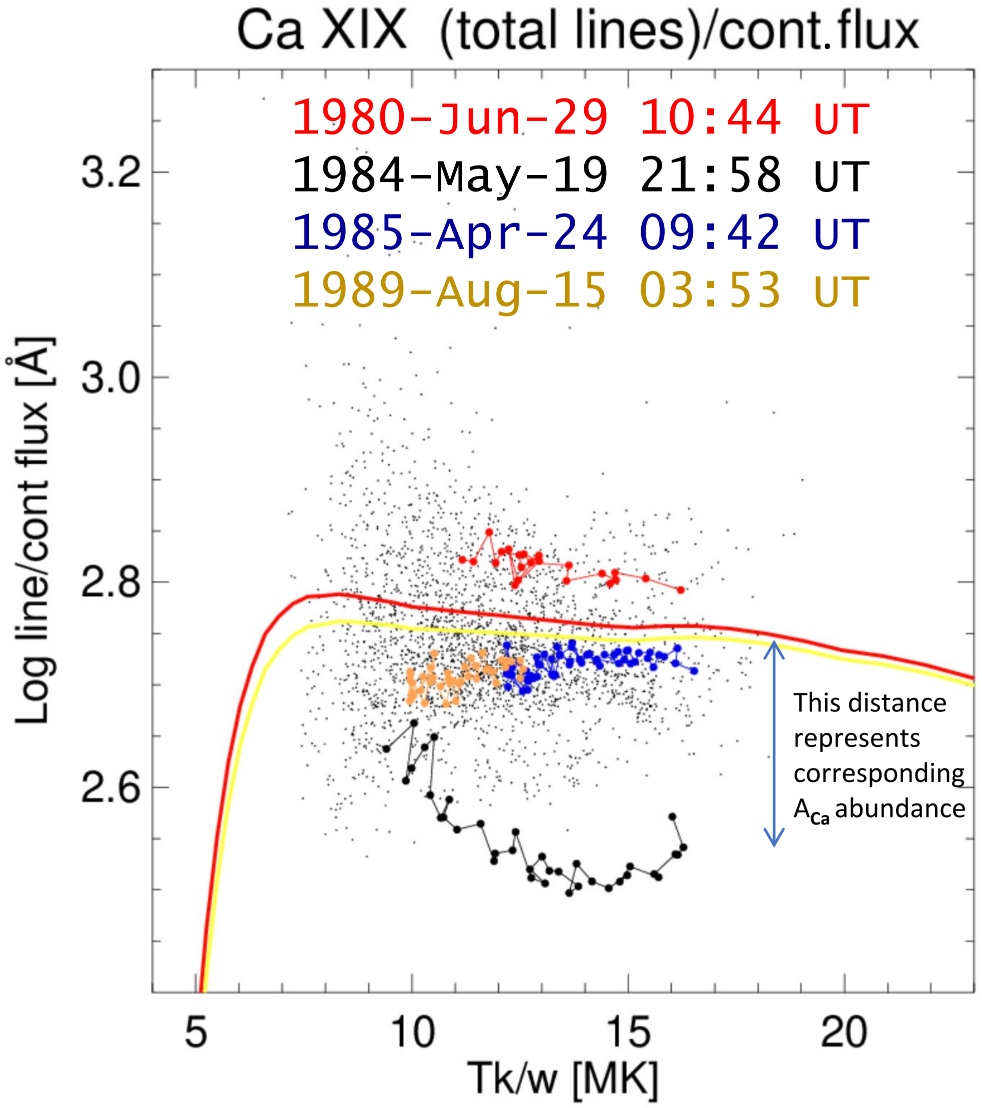
CrossMark

Highly Ionized Calcium and Argon X-Ray Spectra from a Large Solar Flare

K. J. H. Phillips[1], J. Sylwester[2], B. Sylwester[2], M. Kowaliński[2], M. Siarkowski[2], W. Trzebiński[2], S. Płocieniak[2], and Z Kordylewski[2]

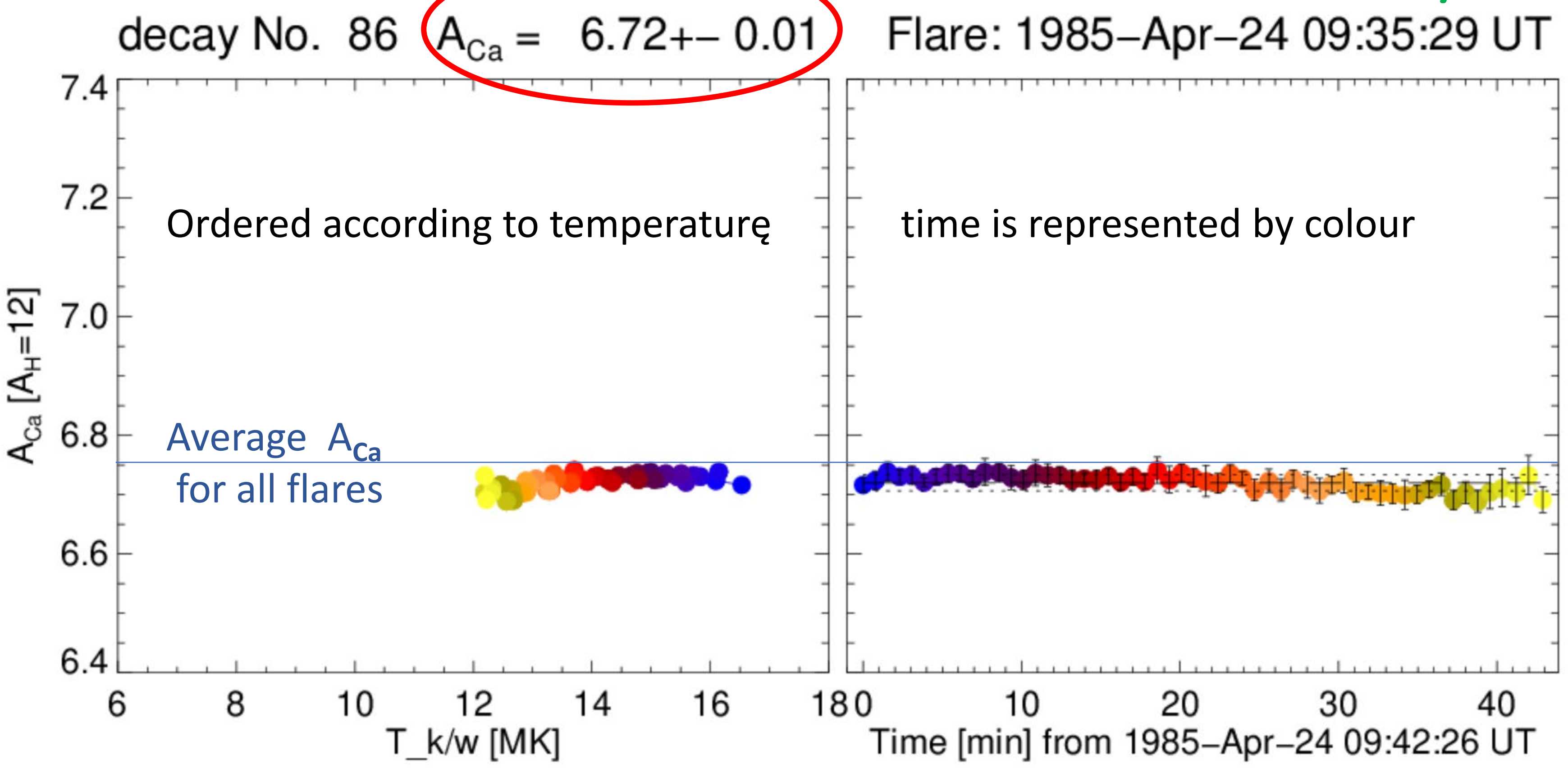
Results: F_T/c ratios for 2806 subintervals



- Individual points represent observed values determined in subintervals
- Smooth lines - theoretical dependences calculated for A_{Ca}=6.76 (average of ~100 flare as taken from the 1998 ApJ Paper)
  - For λ = 3.2257 Å
  - For λ = 3.1723 Å
- Zigzags join in time consecutive points during individual decays of indicated flares
- Note: nearly flat dependence of F_T/c on T
- Overall level of calculated continuum depends slightly on abundance model for other trace elements like Si, S, Fe

A_{Ca} determinations for selected flare decay

more examples will be discussed this Thursday (poster by Barbara Sylwester et al.)



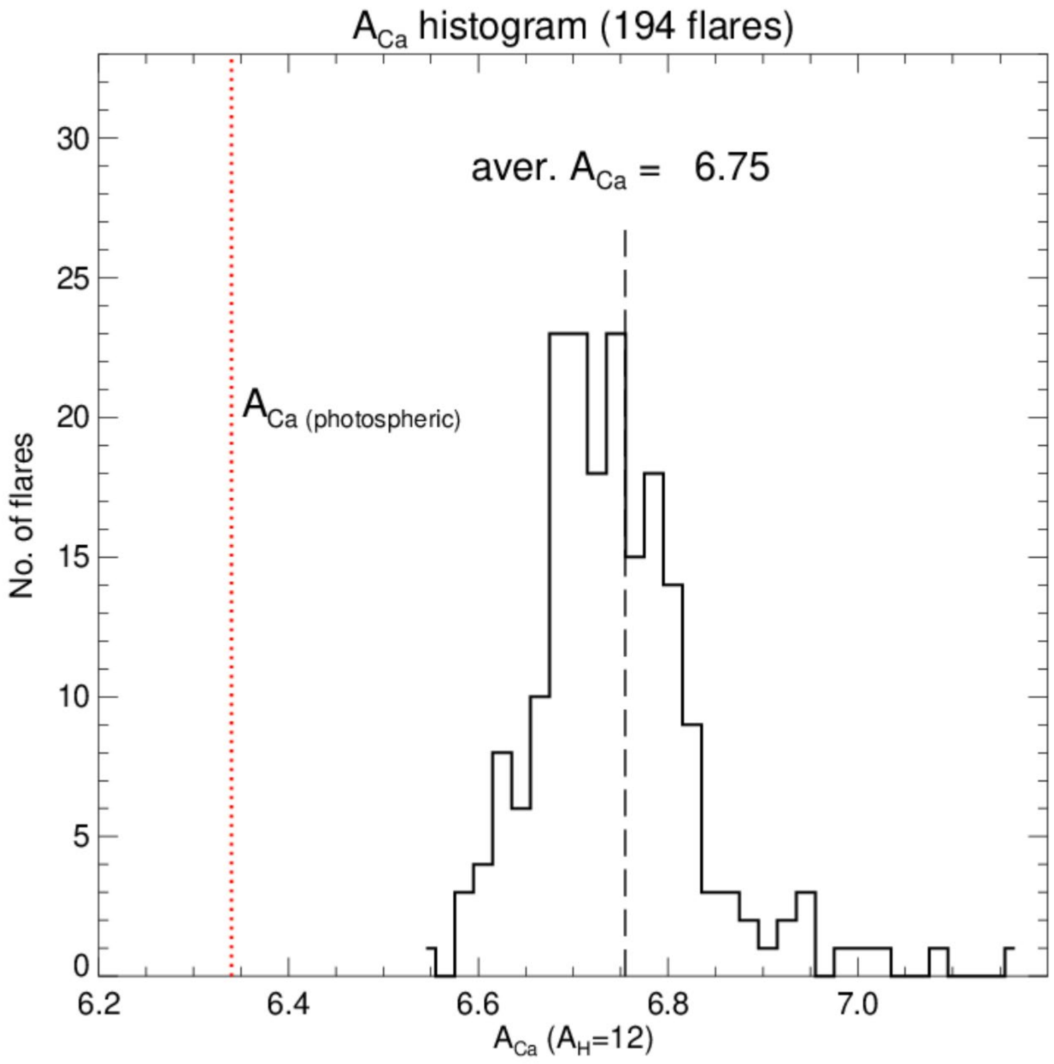
Every colored point represents A_{Ca} value determined for individual subinterval; note small extension of error bars

The accuracy of A_{Ca} absolute determinations reach 2%.

This comes from:

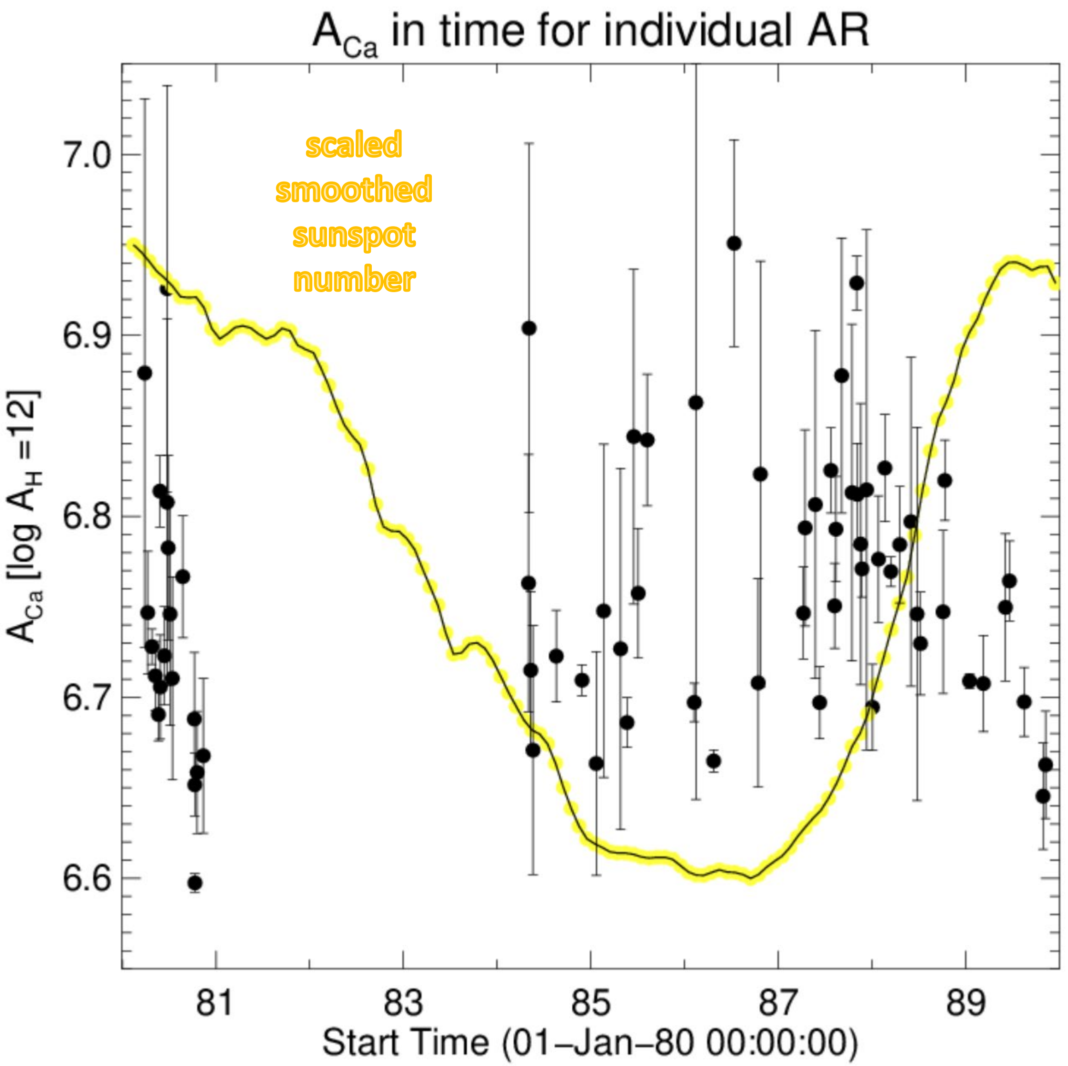
- Better (2-3 times than 1998 Paper) count statistics: total line flux in the range (F_T) is used instead of lone Ca XIX w (F_w) line
- New, more reliable estimates of the continuum level are used (directly determined level instead of fitted level)
- Flat character of theoretical F_T/c on T dependence makes potential temperature errors less influential

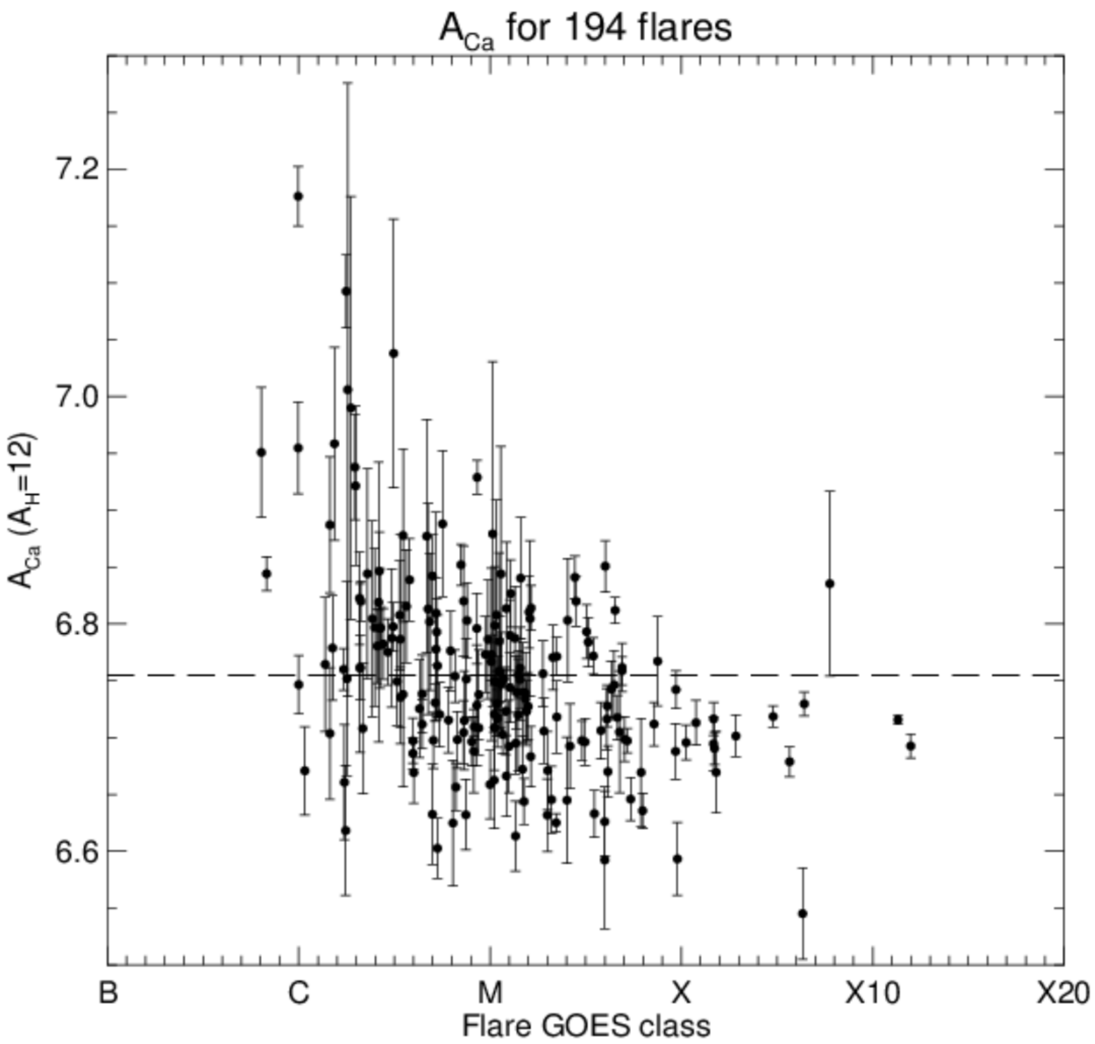
Histogram of A_{Ca} for 194 flares



- Average flare A_{Ca} absolute abundance is ~2 to 3 times the photospheric
- No flares, even the X-ray strongest, have A_{Ca} abundances close to photospheric
- A_{Ca} abundance between flares may differ by a factor up to ~2 ÷ 3
- A_{Ca} abundance for flares from individual AR's tend to cluster around the AR average

Dependence of A_{Ca} on time during Cycles 20 & 21 and on flare class





Summary and Conclusions

- The absolute calcium abundance (A_{Ca}) in coronal flares was obtained from line-to-continuum ratios with high resolution X-ray spectra from the SMM BCS with an accuracy comparable to or better than for UV/visible/infrared spectra.
- The average A_{Ca} in flares is around 2 – 3 times the photospheric A_{Ca}.
- A_{Ca} between individual flares may differ by a factor up to 2 ÷ 3

These results confirm and extend findings of our previous studies (1984, 1998) – the difference being: improved instrument parameters and analysis method for the BCS spectra.

Detailed paper describing the present study is in preparation.

Slides below are kept in order to be shown answering possible questions

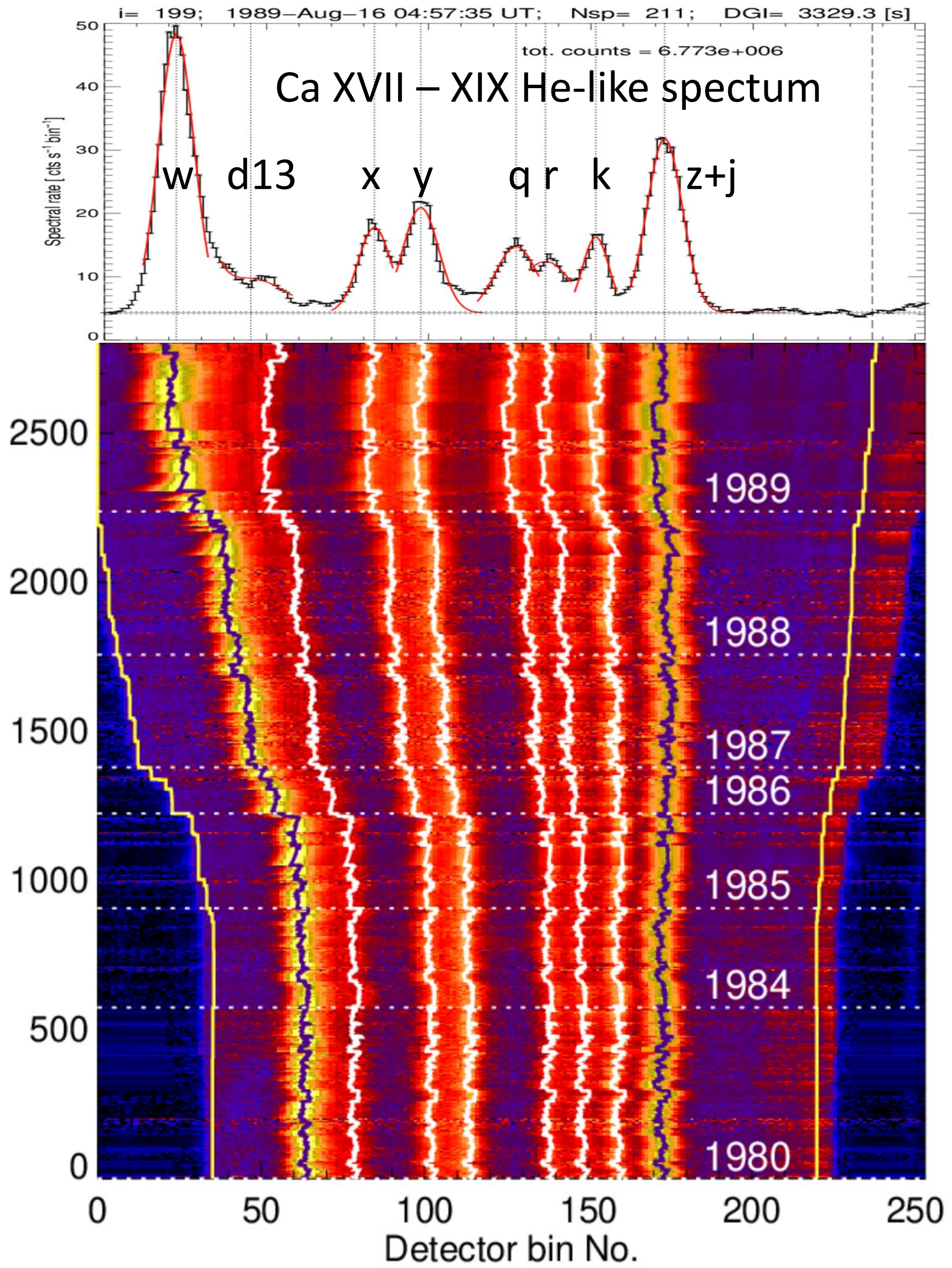


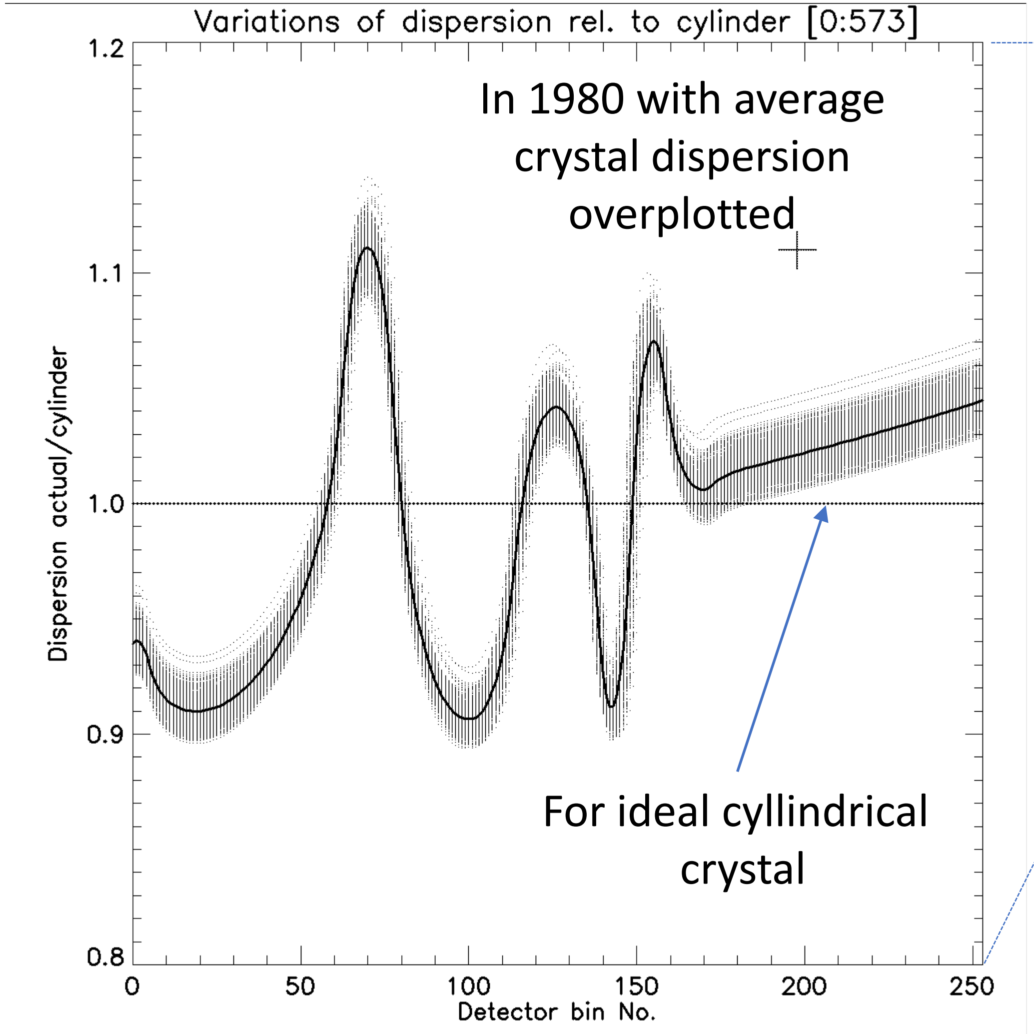
Illustration of BCS detector ageing

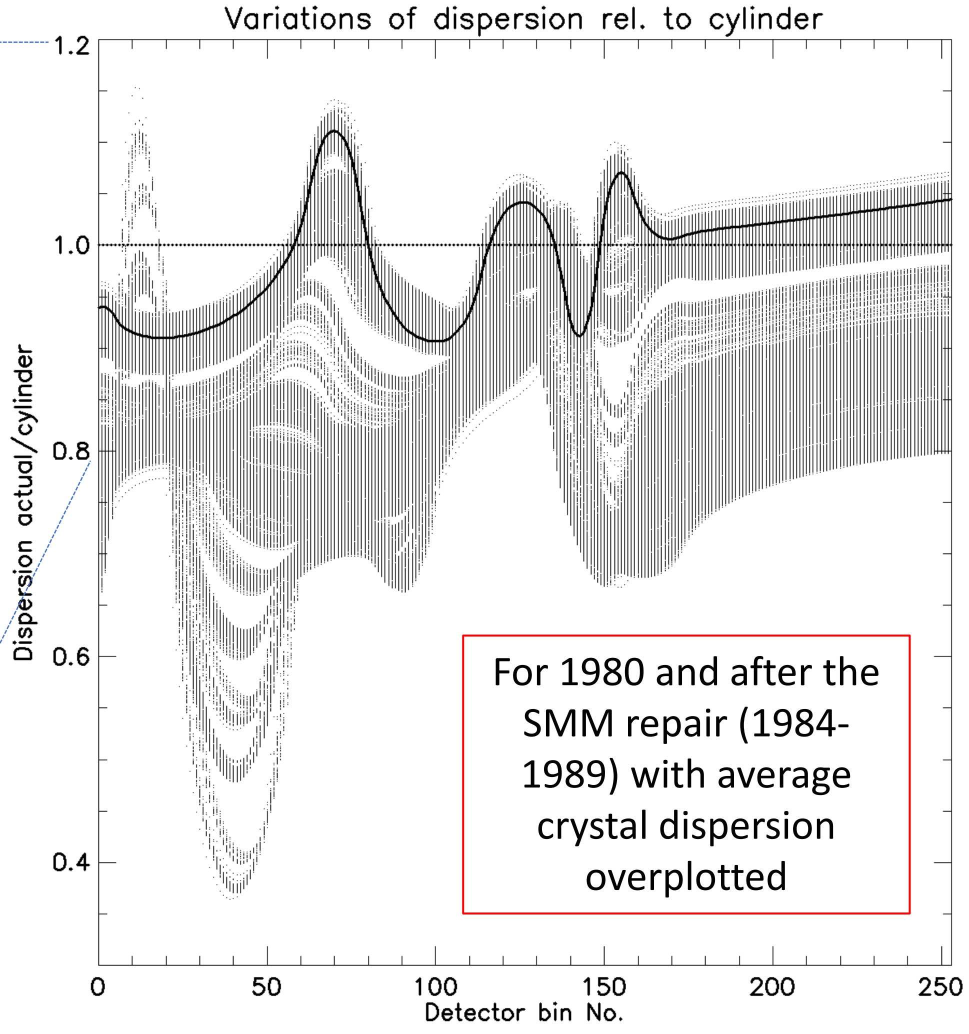
- Observed spectra form modulated signal on detector anode.
- Early in the mission (1980) the line positions depend on Bragg crystal curvature (to be close to cyllindrical shape)
- After 1984 line positions dirft away from z+j blend in both directions
- Central wavelengths of all main (8) lines are precisely known from theory and laboratory (Tokamak plasma) to within 0.0001 Å and were used to translate

  bin's → λ's

  using special smooth time & offset depending relations (IDL min_curve_surf kernel)

Pattern of „dispersion” variations from (bin’s → λ’s evolution)





The continuum observed by BCS in channel 1 is in proportion to GOES flux (f_{gg}) over extended temperaturę range