INFLUENCE OF YOHKOH BCS INSTRUMENTAL SHAPE ON RESULTS OF SPECTRAL FITTING IN VICINITY OF Ca XIX LINES

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ABSTRACT

The analysis of Ca XIX helium-like ion soft X−ray spectra in vicinity of the resonance line at λ=3.177 [Å] proved to be very useful in determinations of calcium absolute abundances. This spectral region have been extensively investigated using Bragg Crystal Spectrometers aboard the *Solar Maximum Mission (SMM)* and *Yohkoh* spacecraft. The analysis of the line-to-continuum intensity ratios yield however conflicting results as concern the average calcium abundance for flares observed by *SMM* and *Yohkoh* spectrometers (Bentley, Sylwester and Lemen, 1997).

In the present research we investigate the influence of possible uncertainties in the shape of instrumental part of the spectral line profile on derived *Yohkoh* abundances. We conclude that by increasing the width of Lorentzian component of the instrumental profile it is possible to lessen the mentioned discrepancy.

Key words: Sun: X-ray; *Yohkoh*; Bragg Crystal Spectrometer; instrumental profile

1. INTRODUCTION

The Bragg, soft X-ray crystal spectrometers developed at MSSL are among the most suitable instruments for detailed study of the solar flare spectra since they allow to measure instantly the entire spectral region covered. The convex crystal spectrometer has been placed aboard the NASA *Solar Maximum Mission* (*SMM*) satellite and collected thousands of flare spectra during 1980 and 1984-1989 periods. Similar concave spectrometer is observing active corona since October 1991 aboard the Japanese *Yohkoh* spacecraft and already collected hundreds of thousands of flare and active region spectra. In the rest of this paper we shall call the *SMM* and *Yohkoh* spectrometers SBCS and YBCS respectively. Several of the soft X-ray wavelength bands measured by SBCS and YBCS are in common (see the instrument description by Culhane et al. (1991). One of these common spectral regions covers wavelengths in vicinity of the prominent resonance line of Ca XIX helium-like ion (λ=3.177 [Å]) including respective shortwavelength continuum. This particular range of X-ray spectrum is especially interesting for studies of the calcium elemental abundance since both the line and continuum emission are formed in hot flaring plasma regions of about the same temperature. This similar temperature dependence of the line and the continuum emission eliminates to large extend the dependence of the line-to-continuum ratio (L/C) on the temperature (for detailed discussion see Sylwester et al., 1999). Based on the interpretation of SBCS spectra we discovered that calcium plasma composition vary between individual flares (Sylwester, Lemen and Mewe, 1984), and noticed for particular active region a trend of average flare calcium abundance to increase with time (Lemen, Sylwester and Bentley, 1986). The early analysis of *Yohkoh* spectra performed by Bentley, Lemen and Sylwester, (1997) confirmed presence of flare-to-flare calcium abundance differences. However a problem has been identified: the average values of absolute Ca abundance as determined from SBCS and YBCS have been found to disagree ($\overline{A_{\rm Ca}}$ = 5.77 ±1.41 and 3.40 ±0.42 for *SMM* and *Yohkoh*) respectively . One may think of a number of factors which may be responsible for the noted difference. One of them can be related with the instrumental shape of the spectrometer. In the present study we adopted heuristic approach and investigated the consequences of varying the Lorentzian width of instrument profile. Presented results indicate that by increasing this width $\sim$ 2.5 times, we optimize the fit of the Ca XIX line wings and rise the $\overline{A_{\rm Ca}}$ value for *Yohkoh* by a factor of $\sim$ 1.56 ±0.3 .

2. FITTING THE BCS SPECTRA - Ca ABUNDANCE DETERMINATION

Determination of absolute calcium abundance from soft X–ray spectra in vicinity of Ca XIX resonance line is a complicated multi-step process involving precise knowledge of the spectrometer and appropriate

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atomic physics. Detailed description of the procedure leading to absolute Ca abundance determinations has been discussed by Sylwester et al. (1999). One of the most important steps in the abundance determination is the fitting of the synthetic spectra to the measured spectral signal. In order to calcu-

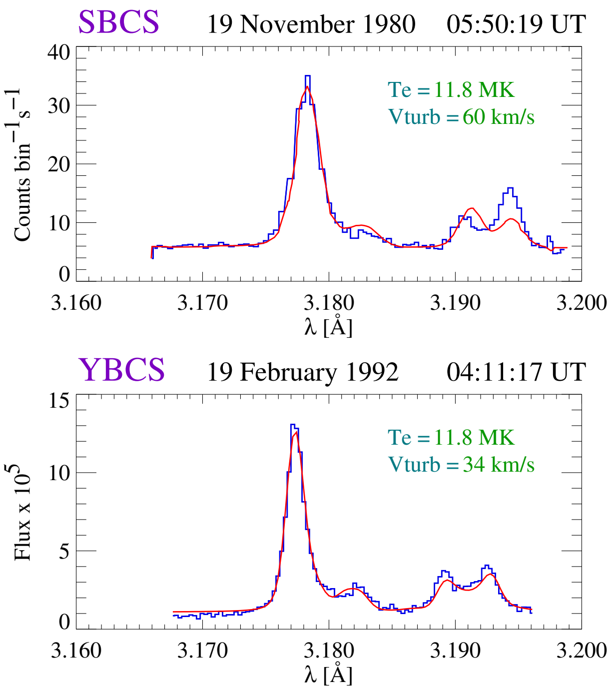

Figure 1. Examples of the spectral fits for SBCS (SMM) and YBCS Yohkoh spectra. Histogram represents the observations and the solid line represents the spectral fit. Only the common range of wavelengths between SBCS and YBCS is shown. The spectra have been selected for times in flares when the plasma temperature was about the same.

late the synthetic spectra the best available atomic data present at the time have been used for *SMM* and *Yohkoh* analyses respectively. The atomic physics factors which are important in spectral synthesis task are:

- ionization fraction calculations,
- excitation rates calculations
- calculations of spectral line positions (wavelengths)

A number of assumptions concerning the physical conditions in the source are normally made:

- the ionization state of plasma is in equilibrium,
- the collision exciters (electrons, protons) have locally Maxwellian distributions
- ion, electron and ionization temperatures (T) are equal
- the bulk and turbulent source plasma motions are known ($V_{\rm d}$ and $V_{\rm turb}$ respectively)

In addition, in order to synthesize the spectrum for a particular spectrometer, the instrument spectral response function (ISRF) is to be known. The shape of ISRF depends on the particular details of the Bragg spectrometer construction. In case of bent spectrometers used aboard SBCS and YBCS the following factors are important:

- the wavelength profile of the rocking curve of the crystal used as disperser
- the combined position readout profile of the position-sensitive detector and following signal processing electronics

It is assumed that the crystal rocking shape can be well approximated by a Voigt profile characterized by respective Lorentzian and Gaussian widths. The position readout profile has been assumed to be of a Gaussian shape.

Instrumental factors responsible for a shape of the ISRF have been carefully measured for both SBCS and YBCS spectrometers and their values which were used in analysis of Ca XIX spectra are put in Table 1

Table 1. Parameters defining instrument widths for SBCS and YBCS.

FWHM width [μÅ]	*SMM* Ca XIX Channel	*Yohkoh* Ca XIX Channel
Lorentzian	0.64*	0.3889
Gaussian		0.2940

* from SMM X-ray Polychromator User's Guide, Lockheed-MSSL-RAL 1980
The value represents the combined Lorentzian and Gaussian widths.

In addition, the observed spectral line profile shape may depend on the extend of the source as projected on the dispersion plane. For SBCS most of these problems are not relevant since the collimator placed in front of the spectrometer (6 × 6 arcmin FWHM) selected only particular active region at which the spectrometer has been pointed at the time of the measurements. In case of YBCS the FOV of the spectrometer covers entire Sun and therefore the source (flare) angular dimension provides "self-collimation" in most cases. However the portion of Ca XIX spectra illuminating the detector depends on the flare position along the dispersion axis (oriented N-S in case of YBCS). This effect is illustrated in Fig. 2. The diagram presented allows for easy identification of the spectral range which would be covered by the YBCS measurements provided that the flare location on the disc is known (and vice versa). It is also seen from the diagram that for flares occurring far South from the equator substantial part of the shortwavelength continuum is present on the recorded spectra.

In order to compare the results of fitting of the synthetic spectra to the measured counterparts for the two spectrometers mentioned one has to understand the differences between the atomic physics used in spectral synthesis and the differences in the spectrometer's construction. Except for the line positions (wavelengths) the atomic physics used in spectral synthesis is consistent between the SBCS and YBCS spectra fitting packages. The differences in line positions between SBCS and YBCS software packages do not influence the results of Ca abundance studies very much.

The observed line widths change during flare and between flares due to evolution of the plasma con-

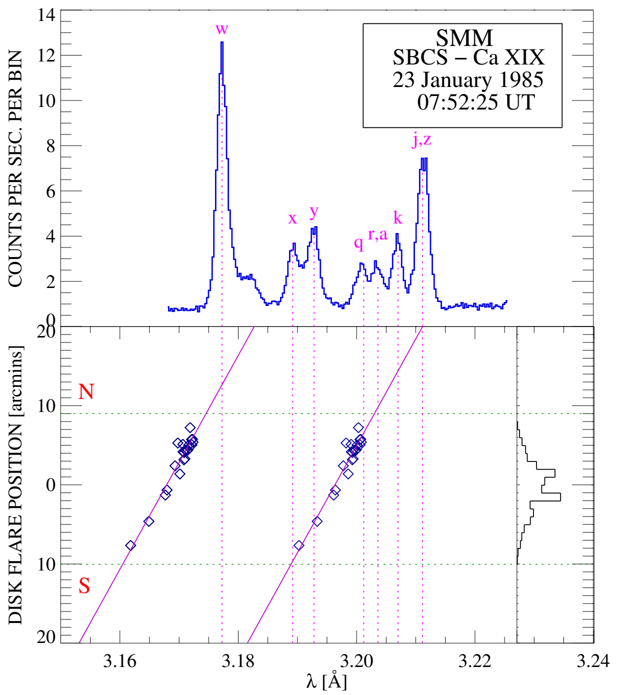

Figure 2. Diagram showing dependence of Ca XIX *spectral coverage on the position of the flare along the YBCS dispersion axis (N-S). The lower panel shows wavelength of the extreme spectral bins observed in the spectra for a set of selected flares. Their respective N-S locations [arcmin] have been taken from appropriate Hα observations. The inclinations of regression lines drawn through the data corresponds to the spectrometer dispersion. At the top panel the example* SMM *spectrum is plotted for the comparison. The histogram represents distribution of flares positions (as observed along the dispersion axis).*

ditions in the source as the flare progress, The instrument widths are expected not to depend on the source plasma characteristics, except for case of YBCS where detector ionization cascade clumping (ionization avalanche channeling) towards stronger line(s) is observed to become important for flares above M2 GOES importance.

Provided that some uncertainty is present in the values used for instrumental factors, this effect may influence the results of fit of the synthetic spectra in a systematic way. If such effects can be realistically identified this may provide argument for reconsideration of the instrumental factors involved in the synthetic spectra convolution.

3. SELECTION OF FLARES FOR THE STUDY

We concentrate our analysis on the spectra collected during the fall of solar activity cycle 22, since the corresponding SBCS measurements represent the fall of activity cycle 21. We decided to select for detailed analysis (from the *Yohkoh* data set) these observations which correspond to the period between 1 October 1991 and 1 October 1995. From the total of several hundred solar flares observed we have chosen six representative events using the following criteria:

1. Flares have to be observed close to the solar limb (the latitude $> 85^o$).
2. Event's importance has to be below M2 GOES level (in order to avoid problems with the YBCS "photon clumping").
3. Events have to had smooth gradual decay phases.
4. Flare locations should be as far to the solar South as possible ($> 20^o$; for cycle 22) in order to have significant portion of the continuum observed leftside in respect to the resonance line.

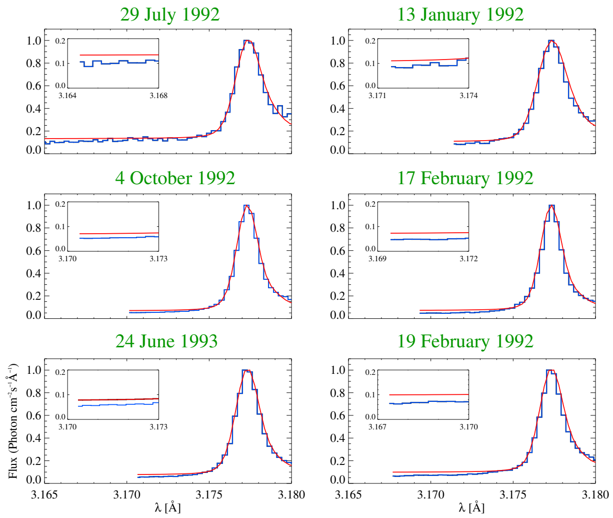

Figure 3. The results of standard spectral fitting for spectra recorded during decay phase of the six flares selected. Histograms represents measured spectral profiles and the continuous line overplotted is the corresponding "best-fitted" synthetic spectra. For each flare the insert shows enlarged portion ($\Delta\lambda$ = 3 [$m\AA$]) of the blue edge of respective observed and fitted spectrum in order to better see the difference. The position of the short-wavelength cut-off depends on the location of the source relative to the YBCS boresight (see Fig.2)

We consider these criteria important based on the following considerations:

Ad. 1. Flares observed at/close to the limb do not show (Antonucci, et al. 1982, Fludra et al, 1989) a strong blue-shifted line component. Therefore "a single spectral component analysis" is, in the most of cases justified and sufficient.

Ad. 2. For flares with GOES class above ~M2 the YBCS detector appears to pronounce significant instrumental bias changing the observed line profile (the effect named "photon clumping"). Therefore for a detailed study of line profiles it is safer to work with spectra recorded at the times when flare importance have been below this ~M2 threshold.

Ad. 3. It is known (Antonucci et al., 1982, Fludra

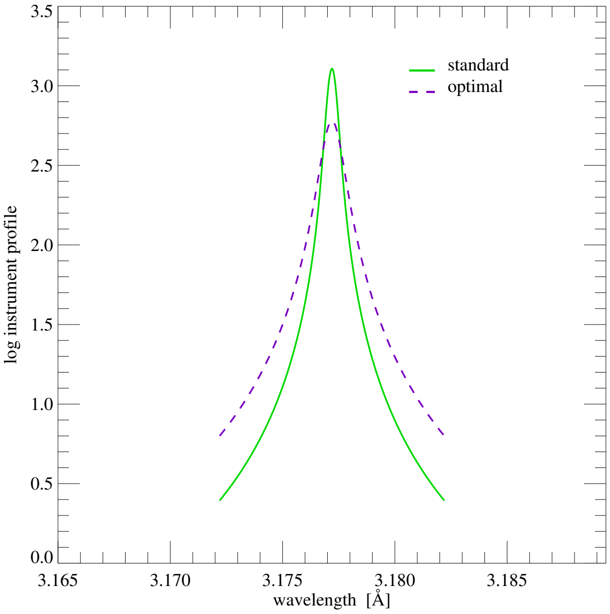

Figure 4. Comparison of the "standard" (continuous) and "optimum" (dashed) shapes of the instrument broadening profile depicted in the logarithmic scale. The "standard" curve corresponds to the Voigt profile calculated using the FWHM widths as in Table 1. (for Yohkoh). The "optimum" represents the shape calculated assuming the Lorentzian width of $1[m\AA]$*, i.e factor 2.5 greater.*

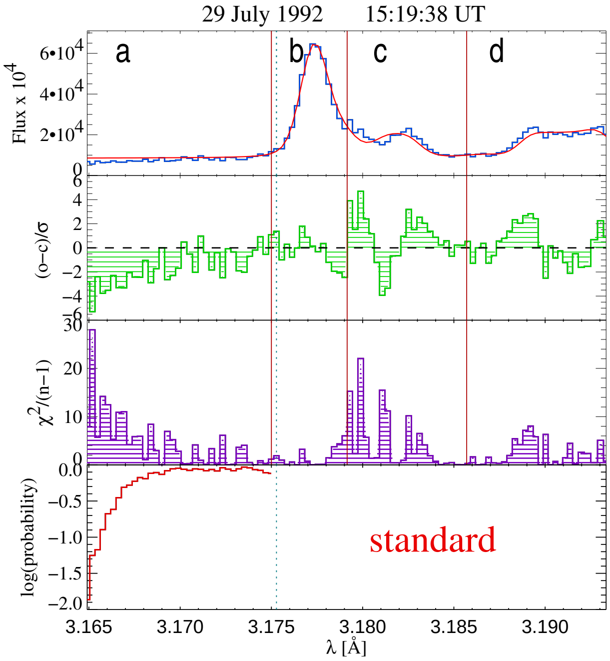

Figure 5. Spectral ranges selected for the analysis of the quality of the fit. Ranges **a**, **b** *and* **c** *are of interest for the present study. The middle upper panel shows the difference of the observed and fitted spectra expressed in terms of the measurement uncertainty. Middle bottom is the difference expressed in terms of* χ^2. *In the bottom panel results of* χ^2 *goodness of the fit are presented. They represent the logarithm of probability that the present fit model accommodate the observed spectra while extending the area of comparison towards the shortwavelength end of the observed spectral range.*

et al, 1989) that during the gradual phase of flares, the turbulent broadening of spectral lines is usually much less than that observed during the rise phase. Turbulent broadening contributes effectively to the observed line profile for YBCS an SBCS and therefore, in order to lessen related effects, we have selected for the analysis the spectra recorded during *decay* flare phase only. This selection has been also applied in the analysis of the *SMM* spectra discussed in Sylwester et. al., (1999).

Ad. 4. By selecting flares far South from the equator, we are able to investigate the quality of fitting for the far wings. For most of *Yohkoh* flares only small portion of the continuum is observed as follows from the diagram shown in Fig. 2 (cf. the flare distribution along the N-S direction represented as vertical histogram).

While fitting the YBCS spectra we have applied standard procedures described in detail by Fludra et al., (1989). In this respect we have used standard fitting routines available in the SOLAR_SOFT analysis package (FIT_BCS). In Fig. 3. we present examples of the fit to the decay phase spectra for the six flares used in the present analysis. It is clearly seen that the fit does not follow the observed spectra in the far wings. The fit to the wings is usually several percent above the observed level. We did worry on this apparent discrepancy and decided to investigate the possibility that the instrument line profile used within a fitting routine is somewhat uncertain. In this respect, we forced to vary the Lorentzian part of the Voigt instrument profile and investigated consequences of such a change. In Fig. 4 we illustrate how sensitive is the shape of the instrument profile to the assumed width of the Lorentzian component. We felt ourselves somewhat uneasy adopting the strategy of changing the laboratory calibrated widths of the instrument profiles. However, we have been even more dissatisfied with the results of testing the "null" hypothesis that the standard fitting routine "as is" gives a reasonable description of the observed wings of the resonance line.

In Fig. 5 we present results of a rigid statistical test showing that the results of the fit using standard shape of the instrument profile are much beyond the level to be acceptable. While looking towards the far wings, the probability that the present model is able to reproduce the spectra measured is declining dramatically. It should be noted that the test results become unacceptable for the regions far from the line centre. For most of flares (which happen to occur in the active belt), the failure of the fit cannot be actually traced - the results seem satisfactory, since the observed spectra does not extent far enough towards the wings. This formal can actually provide misleading info. As proven, the fitting "as is" fails to fit the far going wings and based simply on this argument we may put in doubt the results of spectral fitting for all *Yohkoh* observed Ca XIX spectra.

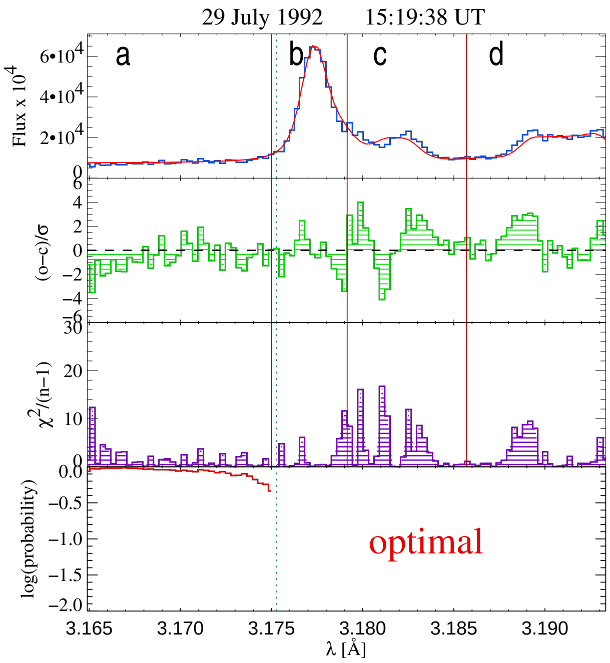

Figure 6. The same as in Fig. 5 except that the optimum values for the width of the Lorentzian component has been assumed. Substantial improvement of the quality of the fit is observed for regions far from the line centre. The results of statistical verification of such a model does not provide arguments for rejecting this hypothesis.

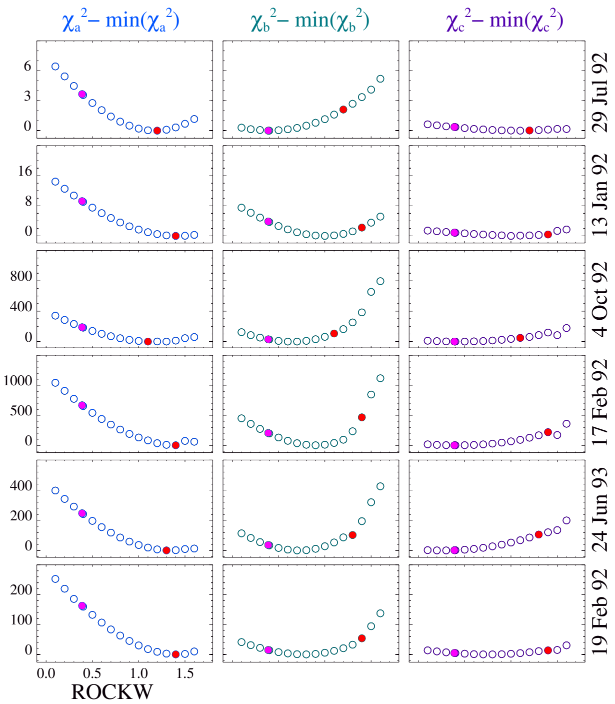

Figure 7. The results of χ^2 goodness of the fit for three spectral regions depicted in Fig. 4. We allowed the Lorentzian part of the line width (ROCKW) to vary and be a parameter. The units in the horizontal axes are [mÅ].

In order to relieve the discomfort of using the fitting procedure "as is", we looked for ways to improve the quality of the fit in the far wings. As mentioned, we allowed the Lorentzian part of the instrument profile to be a parameter. In Fig. 7 we present the results of such exercise for the three spectral ranges labeled **a**, **b** and **c** in Fig. 5. Range **a** represents the fit quality (normalized χ^2) for the far wing spectral region, **b** - the region containing the main line and **c** - the region with the satellite lines of importance for the determination of plasma temperature. It is clearly seen that optimum fit to the line wings is achieved when the Lorentzian width of the instrument profile is ~ 2.5 times the standard. This is the typical behavior for all spectra investigated.

Based on results presented in Fig. 7, we advocate, that the instrument profile of *Yohkoh* Ca XIX has to be modified. The suggest modification is to increase the width of the Lorentzian component of the spectral shape by a factor of 2.5. This modification will easy the fitting of the far wings of the Ca XIX resonance line and make the fit results more comfortable, as presented in Fig. 6.

Presented arguments seem to indicate that the shape of the instrument profile for the *Yohkoh* Ca XIX channel has to be modified. If so, this will bring consequences on the results of physical interpretation of the spectral fitting. In Fig. 8 we illustrate the effects of changing the width of the Lorentzian component on the values of physical parameters derived using spectral fitting.

It is seen that the most sensitive (as expected) is the "turbulent" width derived. As the instrument line width increases, the value of this parameter assumes zero rapidly. Temperature and emission measure estimates are not affected. Substantial change is seen however for the value of the L/C i.e the plasma Ca abundance. In the right panel of the Figure the mentioned dependence is plotted indicating that changes of the instrumental width (towards the optimum value), are causing the abundance values derived to increase by a factor of ~ 1.5 .

4. CONCLUSIONS

The immediate result of the present study is to put in question the results of laboratory calibration of the *Yohkoh* Ca XIX channel. Additional work has to be done in this area. The possibility of end-to-end calibration of RESIK spectrometer (Sylwester et al., 1998) will create the opportunity. Provided that the instrument profile has to be changed, the values of abundances obtained from the analysis of *Yohkoh* data have to be proportionally increased by a factor of 1.56. This change will bring the average abundances of Ca as determined from YBCS up closer to the value derived from *SMM* spectra. These average abundance values are still disparate and the further work is necessary in order to find the reasons for the disagreement left.

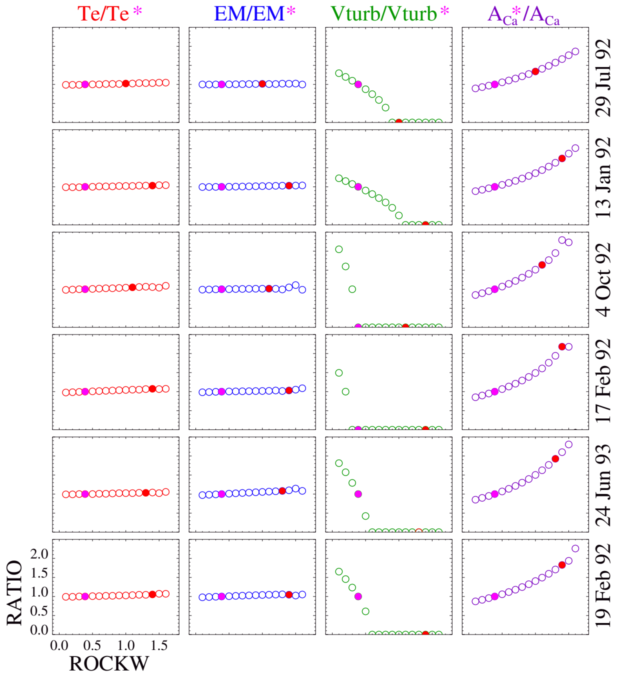

Figure 8. Dependence of the derived source plasma characteristics on the width of the Lorentzian component of the instrument function. Notice the dependence for the derived abundance value. The vertical scale is the same for all plots.

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