Determination of coronal plasma densities from Coronas observations

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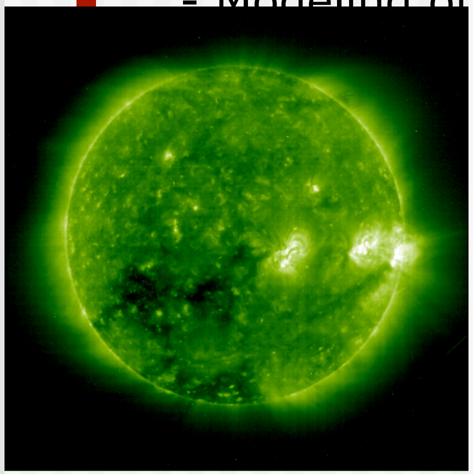
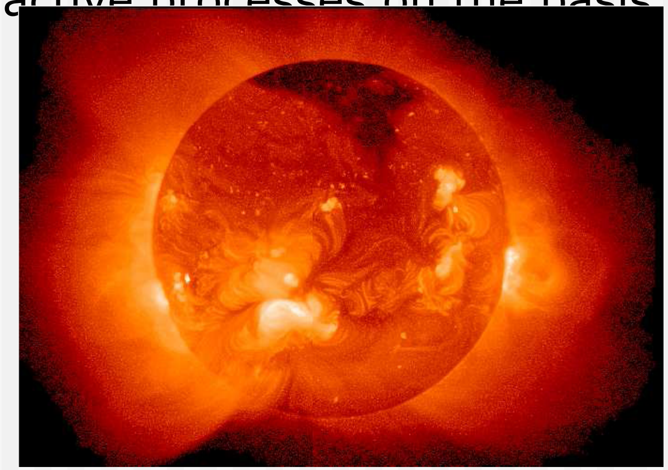
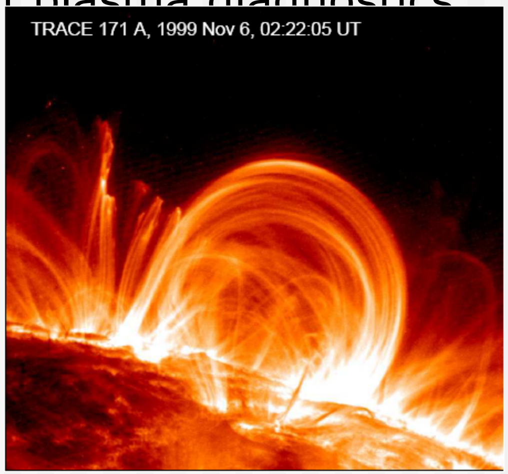
The main problems of solar corona physics

- **Mechanism(s)** of energy release **(where and how?)**
- and its transformation to thermal heating, radiation, acceleration
- of charge particles and plasma motion **("energy budget")**
- - Mechanisms of active phenomena (local processes)
- - Mechanisms of coronal heating and solar wind accelaration
- - Interconnection of local and global processes
- - Modeling of active processes on the basis of plasma diagnostics



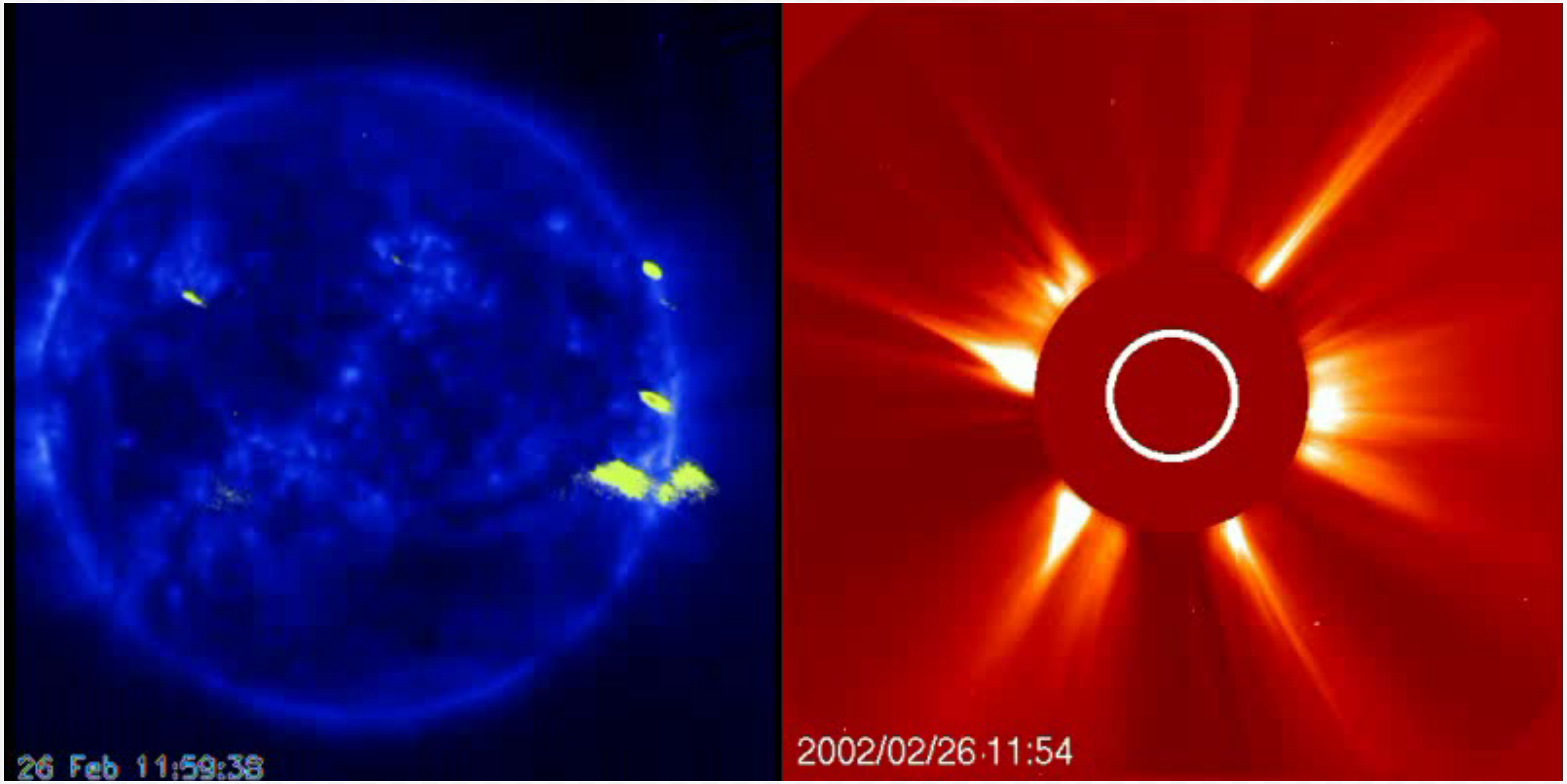




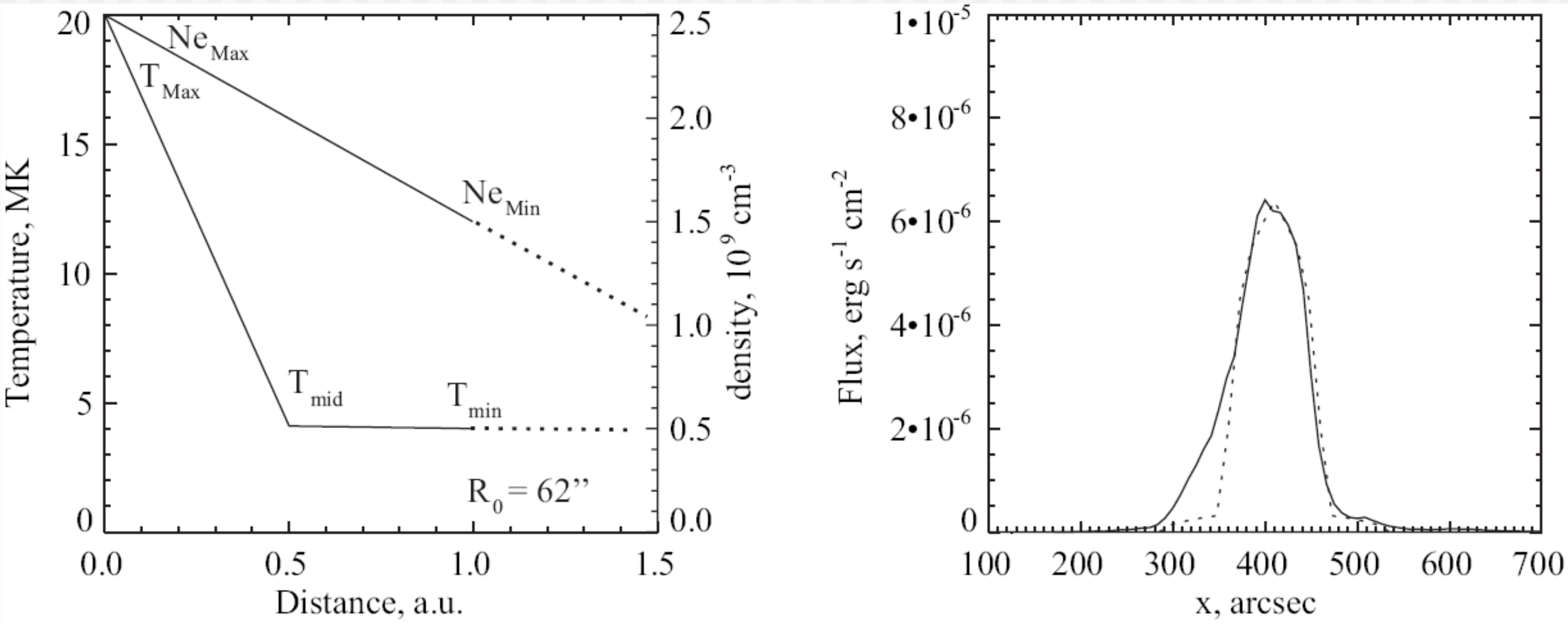
Solar active phenomena

- \- **Relatively stable plasma structures:** active regions (AR), bright points (BP), coronal condensations (CC), characterized by the size of ~ 1 – 5 arc min and life time of ~ 1 – 30 days
- \- **Eruptive phenomena**: flares (F), CME, and others, characterized by the size of 0.1 – 2 arc min and life time of ~ 1 min – 10 hours

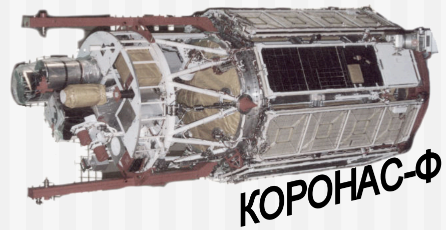
SXR images: MgXII 8.42 A CORONAS-F/SPIRIT



Space modeling for the “spider”

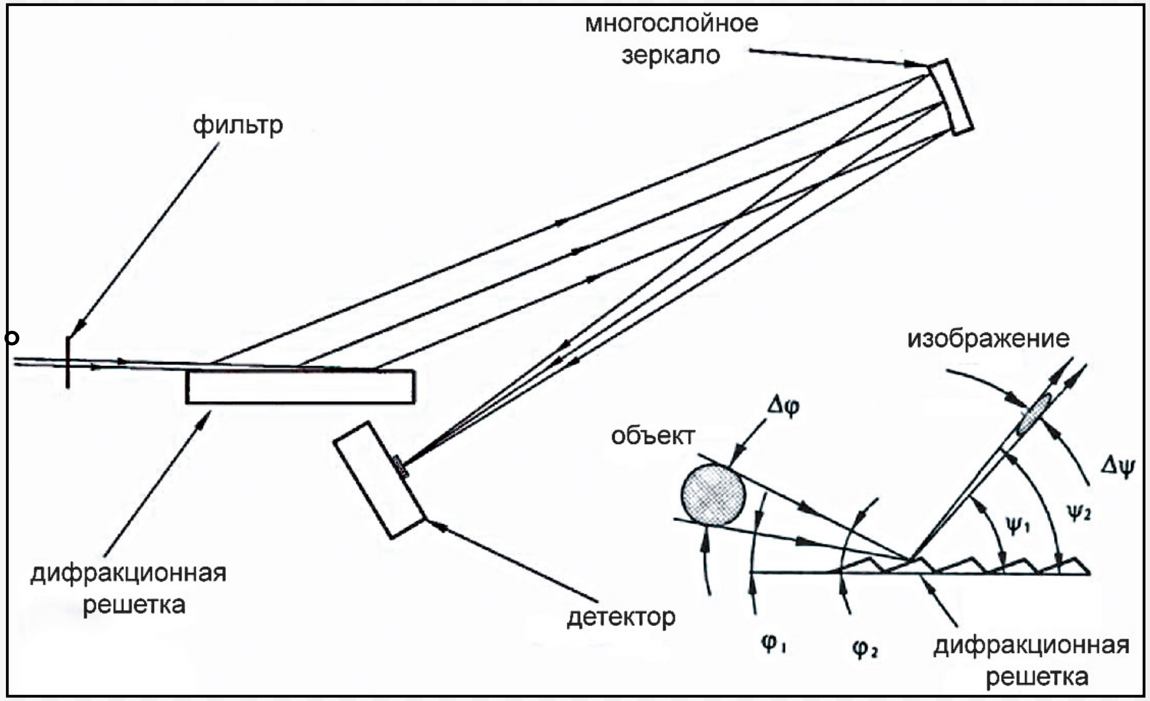


Spectroheliograph RES (SPIRIT)



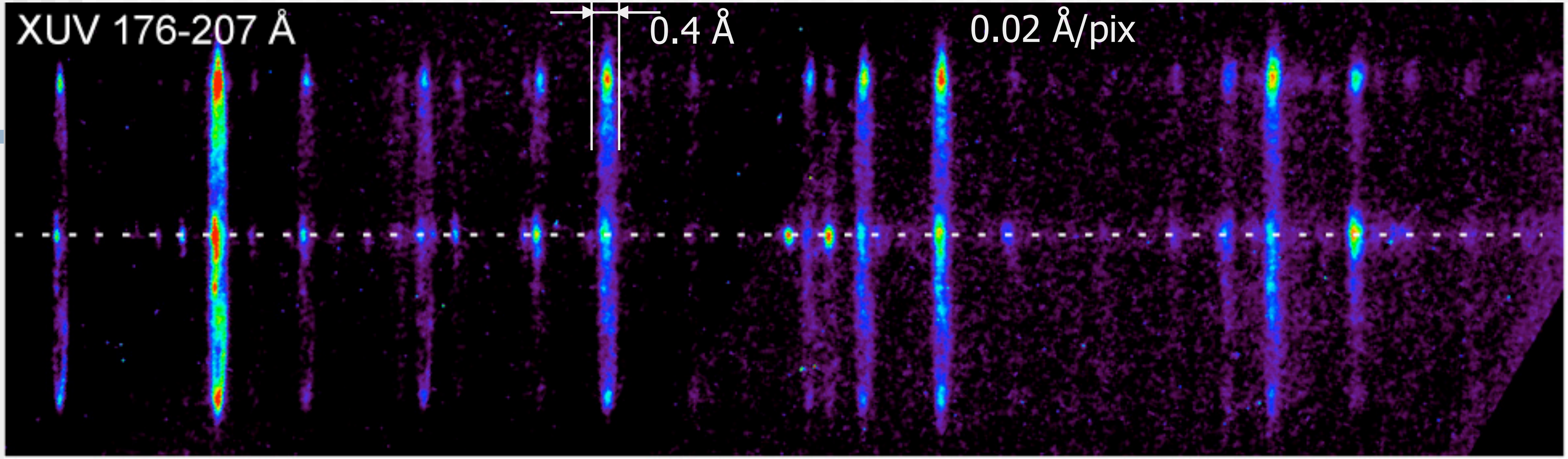
- Two EUV channels:

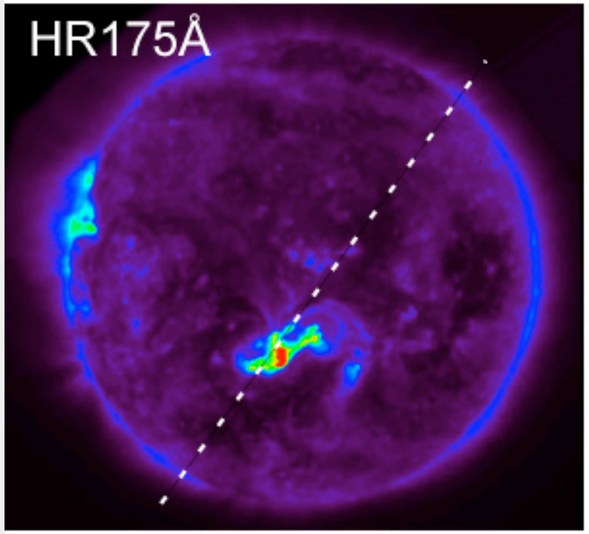
  176-207 Å и 275-335 Å
- slitless scheme
- Grating with incidence angle ~1.5°
- multilayer mirror Mo-Si
- CCD detector

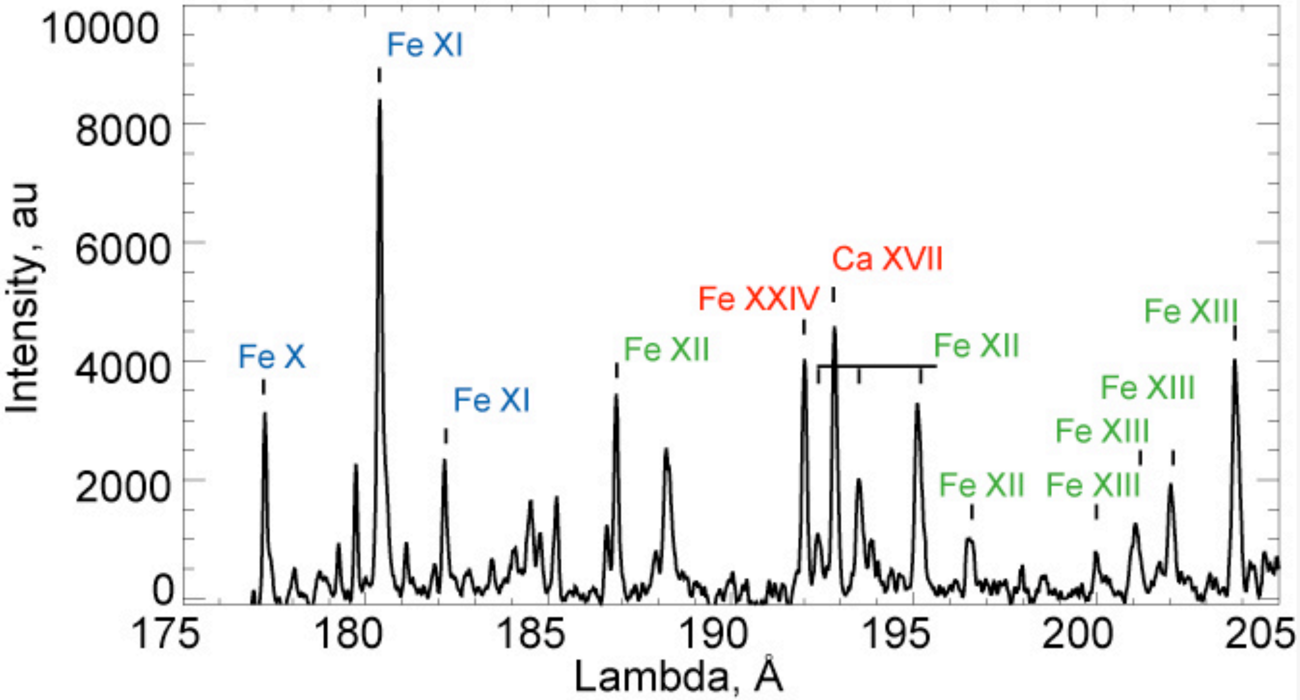


Region: 176-207 Å

СПИРИТ 2005-09-13 21:19 UT X17 (GOES)







RES data

A few tens of thousands of EUV spectroheliograms including 14 powerfull flares of X class

Present representation contain 28 images:

- Quiet Sun areas (QS):

  11/02/2002, 04/03/2002, 16/07/2004

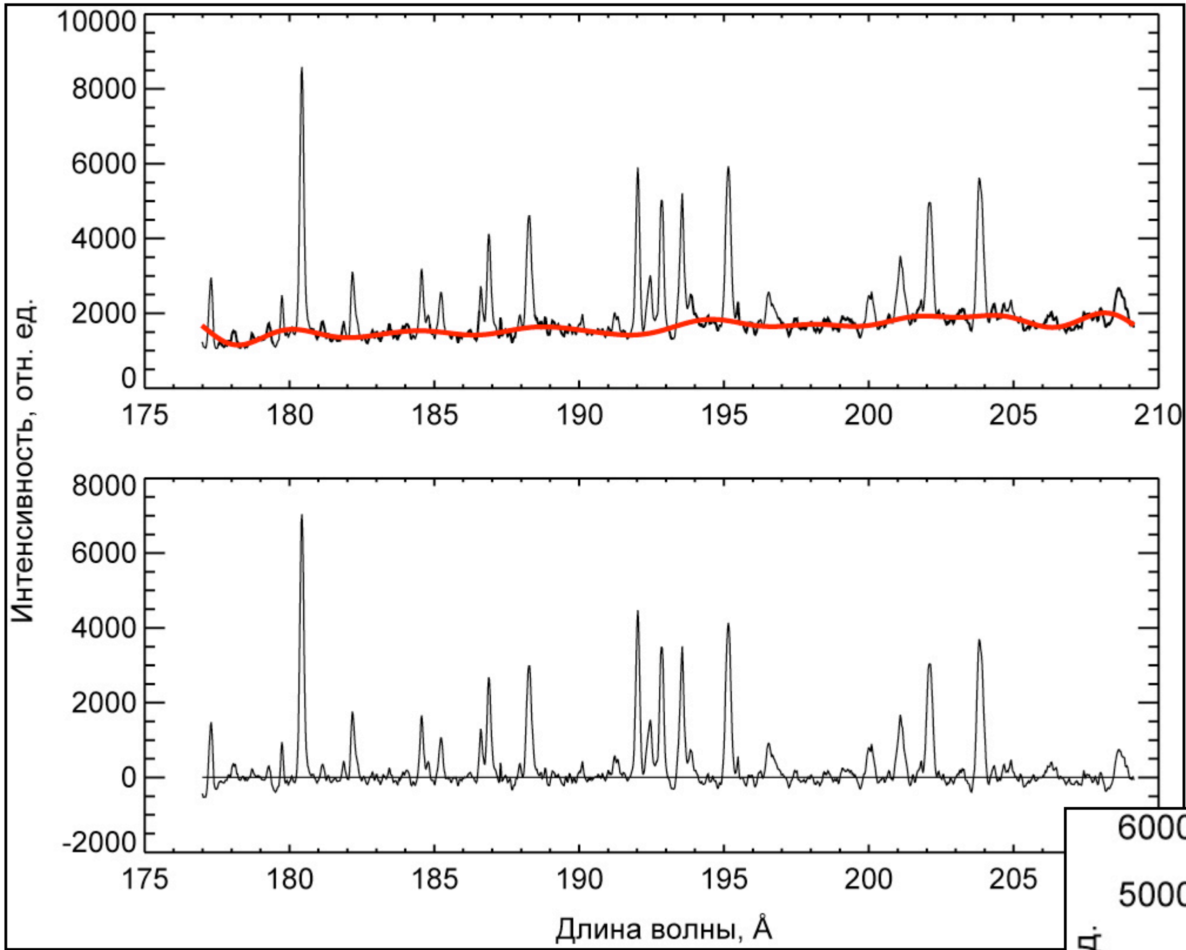
- Active regions (AR):

  02/10/2001, 11/02/2002, 07/06/2002, 17/06/2002, 21/08/2002, 21/08/2002, 06/09/2005

- Off-limb region: 06/09/2005

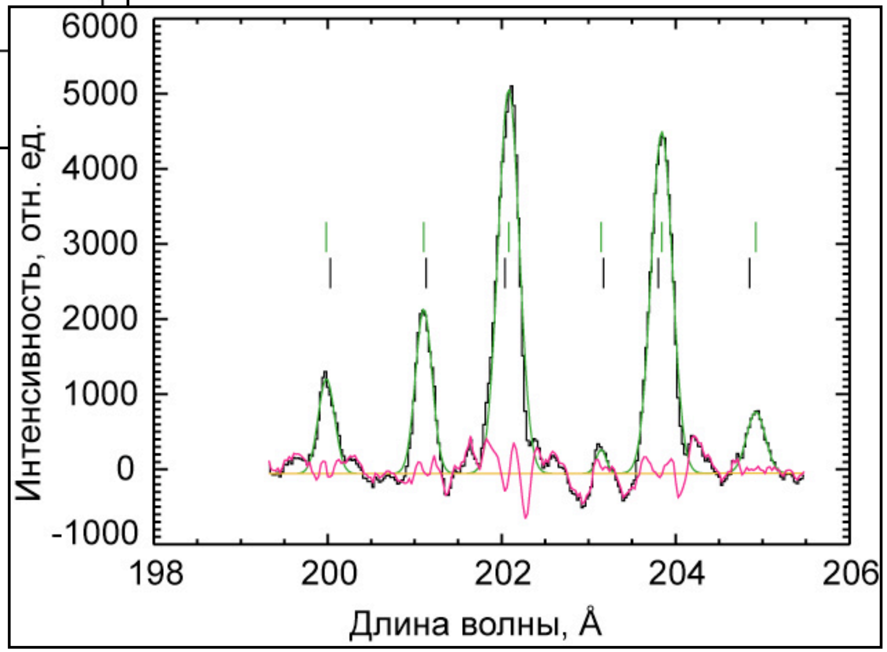
- Flares of M-class: 11/09/2005 – M3.2, 16/09/2005 – M4.8

- Flares of X-class: 16/07/2004 – X1.4, 07/09/2005 – X17 (3 images), 08/09/2005 – X5.5 (2 images), 09/09/2005 – X6.2 (2 images), 13/09/2005 – X1.5 (2 images)



Clearence & Calibration

(Shestov et al., Astronomy letters, v.54, 2009)

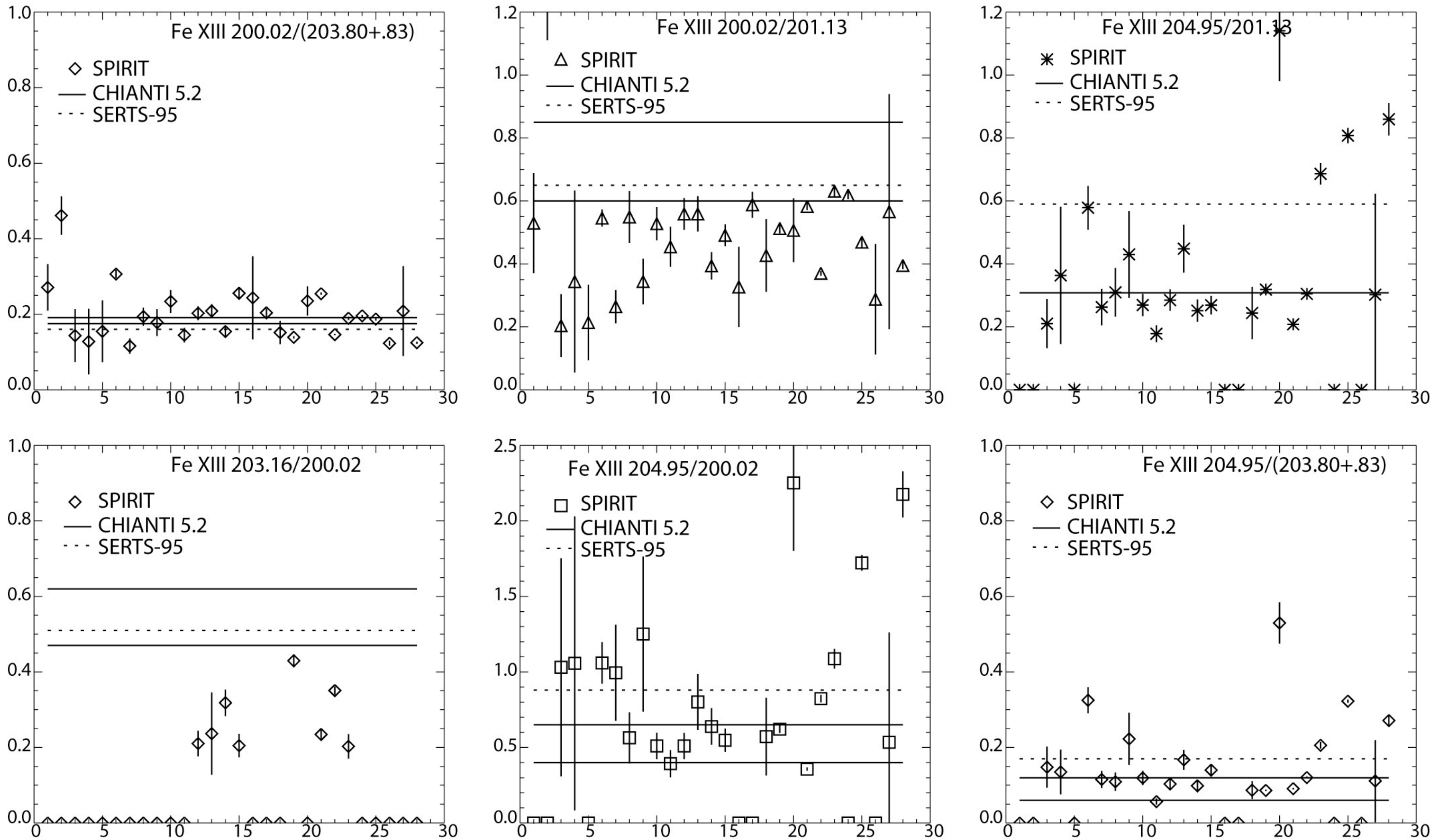


«Fitting»:

$$i(\lambda) = P + Q(\lambda) + \sum_j A_j \exp\left(-\frac{1}{2}\left(\frac{\lambda - \lambda_0^j}{\sigma_j}\right)^2\right)$$

$$\lambda = [\lambda_1, \lambda_2]$$

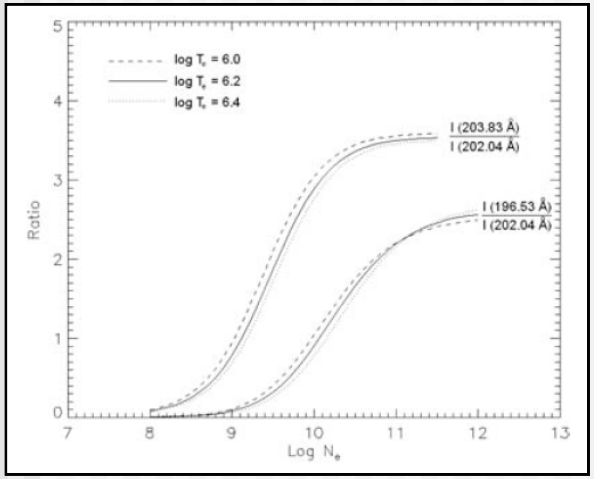
FeXIII Line ratios, used to check calibration



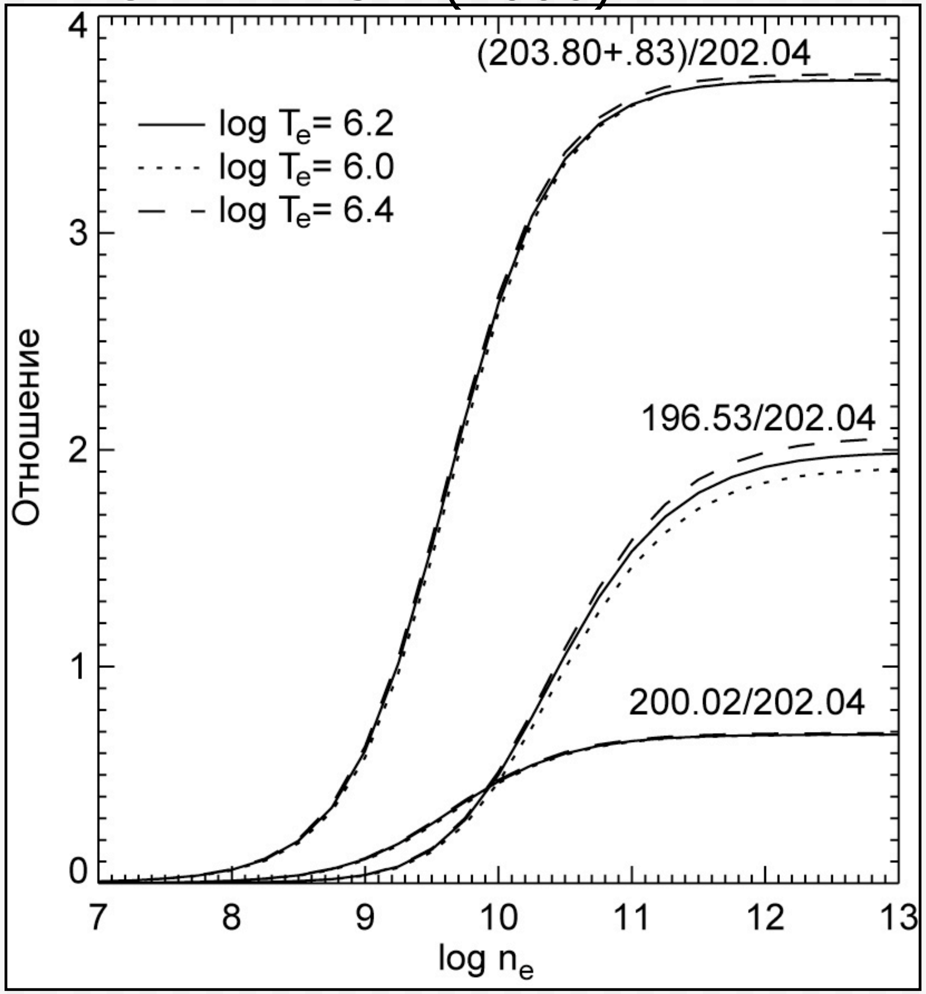
Density determination by Fe XIII lines

- «Strong» lines
- Large interval of density

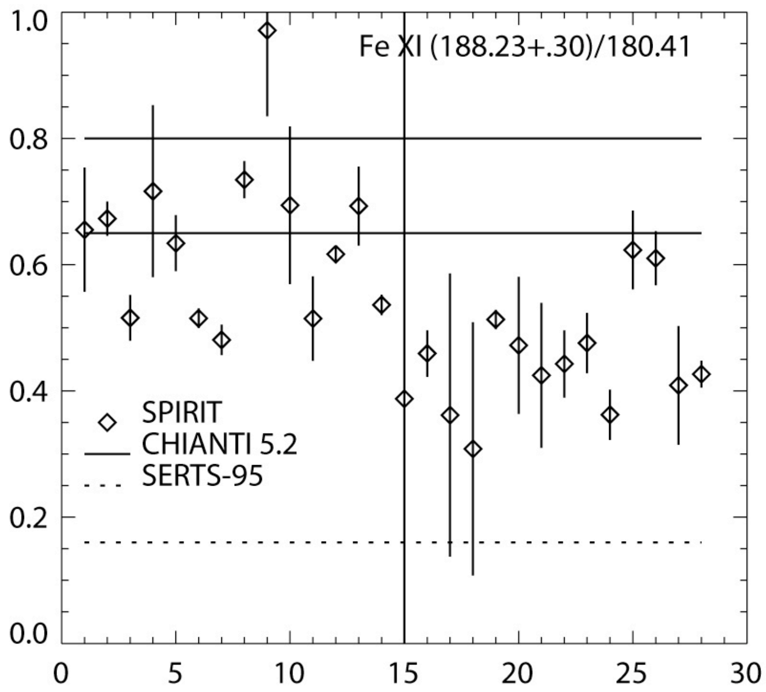
- An error - 0.2 dex at different temperatures (recent calculations by Keenan et al., 2007)

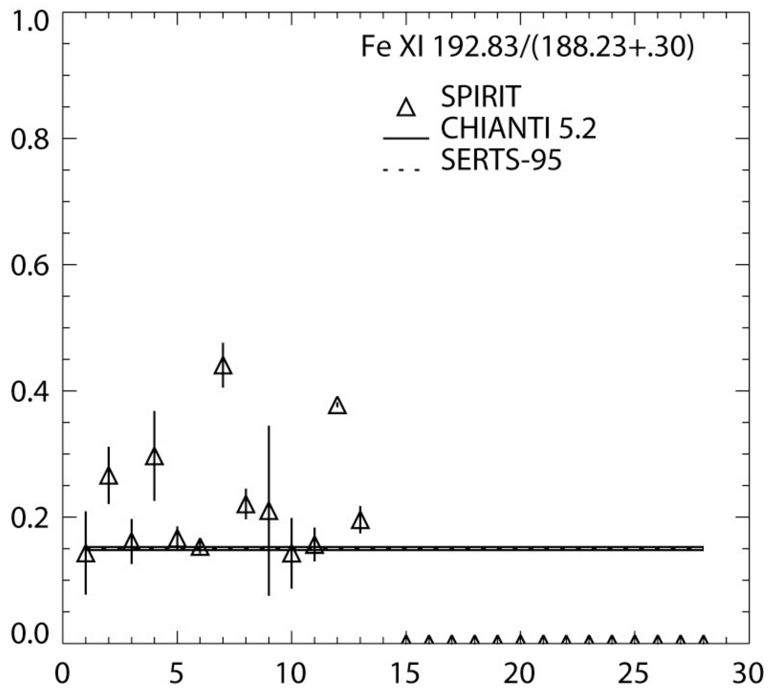


CHIANTI 5.2 (2006)



FeXI line ratios, used to check calibration



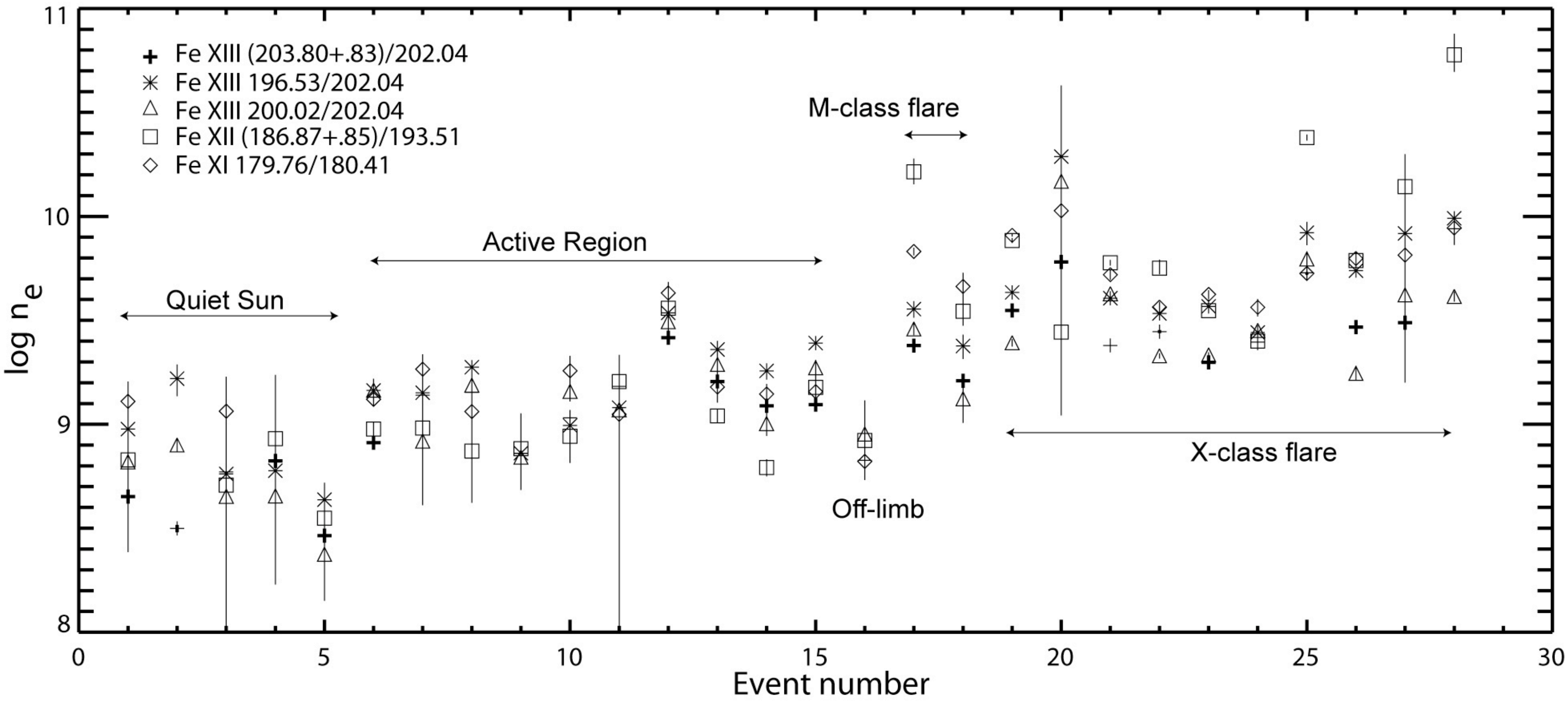


Lines used for density determination:

Fe XI: 179.76/180.41

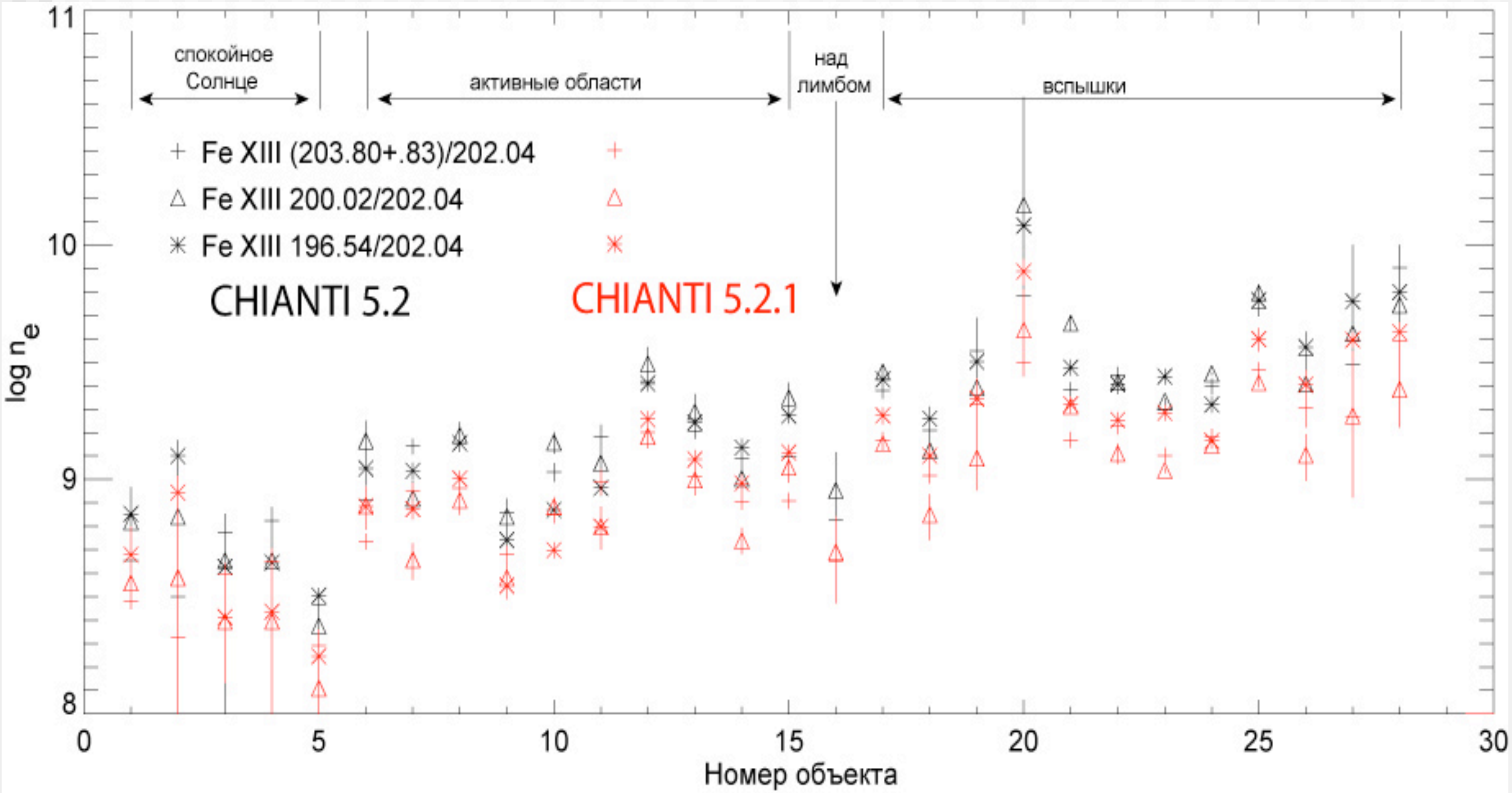
Fe XII: (186.89+.85)/193.51

Densities



Fe XIII (203.80+.83)/202.04
Fe XIII 196.53/202.04
Fe XIII 200.02/202.04
Fe XII (186.87+.85)/193.51
Fe XI 179.76/180.41
Quiet Sun
Active Region
M-class flare
Off-limb
X-class flare
log n_e
Event number
11
10
9
8
0
5
10
15
20
25
30

New version: CHIANTI 5.2.1



DEM determination

(Urnov ey al., Astronomy letters, v.33, p396,2007)

The spectral flux $I(\lambda, \Delta T)$, W m^{-2} Å^{-1}, from a source with temperature T, MK, in the interval $\Delta T = T_0 - T_m$ is defined by a volume integral of the form

$$I(\lambda, \Delta T) = C \int_{(V)} G(\lambda, T(\mathbf{r}))\, N_e^2(\mathbf{r}) d\mathbf{r}, \qquad (2)$$

$$C = 10^{-3} R^{-2},$$

where $T(\mathbf{r}) = \phi(\mathbf{r})$ is a single-valued function in volume V, $N_e(\mathbf{r})$, cm^{-3}, is the electron density distribution, R, cm is the distance to the source.

DEM

$G(\lambda, T)$, erg m^3 s^{-1} sr^{-1} Å^{-1} is the contribution function that is defined by the spectrum (spectral power) $F(\lambda, T)$ of a unit volume with temperature T and electron density N_e,

$$G(\lambda, T) = F(\lambda, T, N_e)/N_e^2, \qquad (3)$$

and that does not depend on N_e in the coronal approximation.

DEM

If the temperature gradient becomes zero ($\nabla\phi_i = 0$) in regions with volume $V_i \in V$ and temperature T_i, then the integral in (2) can be broken down into the sum of the integrals over regions V_i and a region with $T \in \Delta T$, where ϕ is a piecewise smooth function with a gradient $\nabla\phi \neq 0$ in volume $\widetilde{V} = V - \sum V_i$:

$$I(\lambda, \Delta T) = C\left\{ \int_{\widetilde{V}} G\left(\lambda, T(\mathbf{r})\right) N_e^2(\mathbf{r}) d\mathbf{r} \right. \quad (4)$$

$$\left. + \sum_i G(\lambda, T_i) \int_{V_i} N_e^2(\mathbf{r}) d\mathbf{r} \right\}.$$

DEM

Using the identity for $G(\lambda, T(\mathbf{r}))$

$$G(\lambda, T(\mathbf{r})) = \int_{\Delta T} G(\lambda, T)\{\delta\,(T - \phi(\mathbf{r})) \qquad (5)$$

$$+ \sum_i \delta(T - T_i)\} dT$$

and changing the order of integration, we can formally represent the intensity I as the Stieltjes integral

$$I(\lambda, \Delta T) = C \int_{\Delta T} G(\lambda, T) dY(T) \qquad (6)$$

DEM

with the volume emission measure (EM) $Y(T)$ as an integrating function (nondecreasing and right-hand continuous at points T_i) that is the distribution function of matter with temperature and that is defined by the density of distribution function, the DEM $y(T)$:

$$dY(T) = y(T)dT = [y_c(T) + y_s(T)]\,dT, \quad (7)$$

DEM

$$y_c(T) = \int \delta(T - \phi(\mathbf{r})) N_e^2(\mathbf{r}) d\mathbf{r}, \tag{8}$$

$$y_s(T) = \sum_i Y_i \delta(T - T_i); \tag{9}$$

$$Y_i = Y(T_i) = \int_{V_i} N_e^2(\mathbf{r}) d\mathbf{r},$$

DEM

where the integral in (8) is an integral over the $T = \phi(\mathbf{r})$ surface lying in region $\widetilde{V}$ and specifies a continuous function $y_c(T)$ in interval ΔT, while $y_s(T)$ in (9) is defined by the volume integrals over regions V_i and is a singular function at points T_i. The EM $Y(T)$ can thus be represented as the sum of two terms,

$$Y(T) = Y_c(T) + Y_s(T), \qquad (10)$$

DEM

described, respectively, by piecewise smooth and discontinuous ($Y_s(T)$) functions,

$$Y_c(T) = \int_{\tilde{V}} \Theta(T - \phi(\mathbf{r})) N_e^2(\mathbf{r}) d\mathbf{r} + Y_c(T_0), \quad (11)$$

$$Y_s(T) = \sum_i Y_i \Theta(T - T_i), \quad (12)$$

DEM

Let us also consider the column DEM $\widetilde{y}(x, y; T)$ for an extended source with length Δl along the z axis directed along the line of sight $\mathbf{n}$ and with cross section ΔS defined as the density of column EM distribution function $\widetilde{Y}(x, y; T)$:

$$\widetilde{y}(x, y; T) = \frac{d\widetilde{Y}(x, y; T)}{dT} = \widetilde{y}_c(x, y; T) + \widetilde{y}_s(x, y; T), \tag{13}$$

DEM

where the continuous function $\widetilde{y}_c(x, y; T)$ is specified at point $\mathbf{r} = (x, y, z)$ on the $z = z(x, y; T)$ surface:

$$\widetilde{y}_c(x, y; T) = \int_{\Delta l} \delta(T - \phi(\mathbf{r})) N_e^2(\mathbf{r}) dz \qquad (14)$$

$$= \frac{N_e^2(\mathbf{r})}{|(\mathbf{n} \bigtriangledown \phi)|} = N_e^2(\mathbf{r}) \left| \frac{\partial \phi(\mathbf{r})}{\partial z} \right|^{-1},$$

DEM

$$\widetilde{y}_{\rm av}(x,y,z(T)) = \langle \widetilde{y}_c(x,y,z(T))\rangle_{\delta T} \qquad (18)$$

$$= \left|\frac{\partial T}{\partial z}\right|^{-1} \left\langle N_e^2(\mathbf{r})\right\rangle_{\delta l},$$

$$\widetilde{Y}_{\rm av}(T) = \left\langle \widetilde{y}_{\rm c\,p}(x,y,z(T))\right\rangle_{\Delta S} \qquad (19)$$

$$= \left\langle N_e^2(\mathbf{r})\right\rangle_{\Delta V},$$

DEM reconstruction

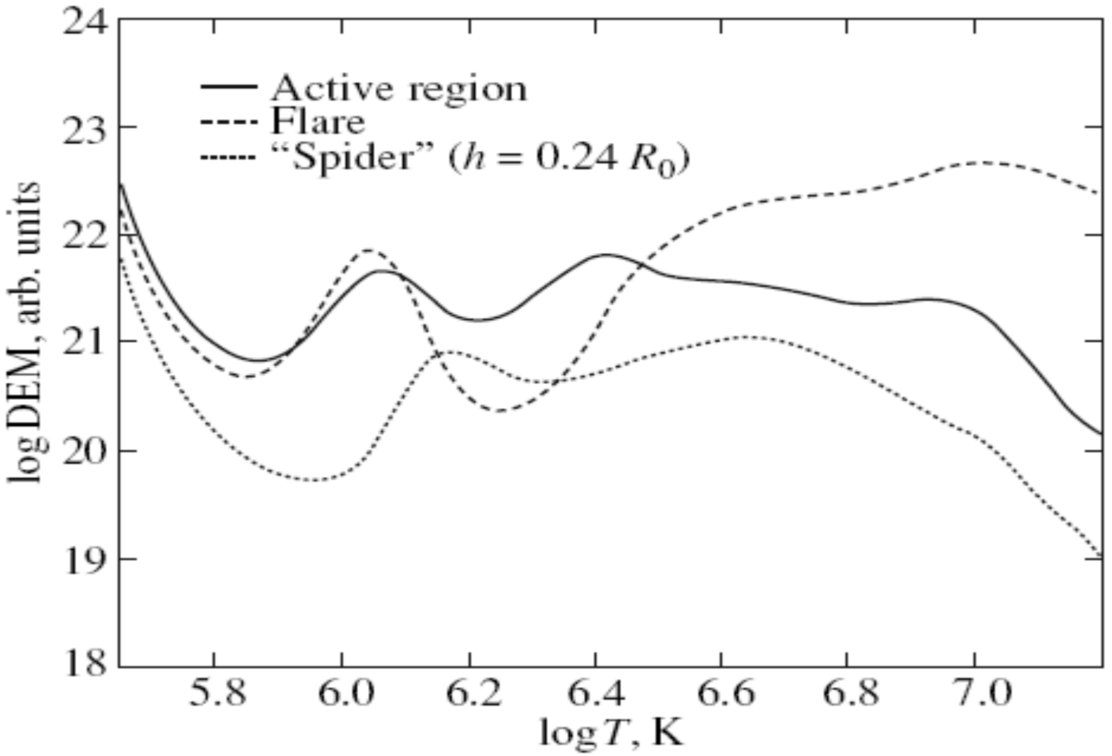
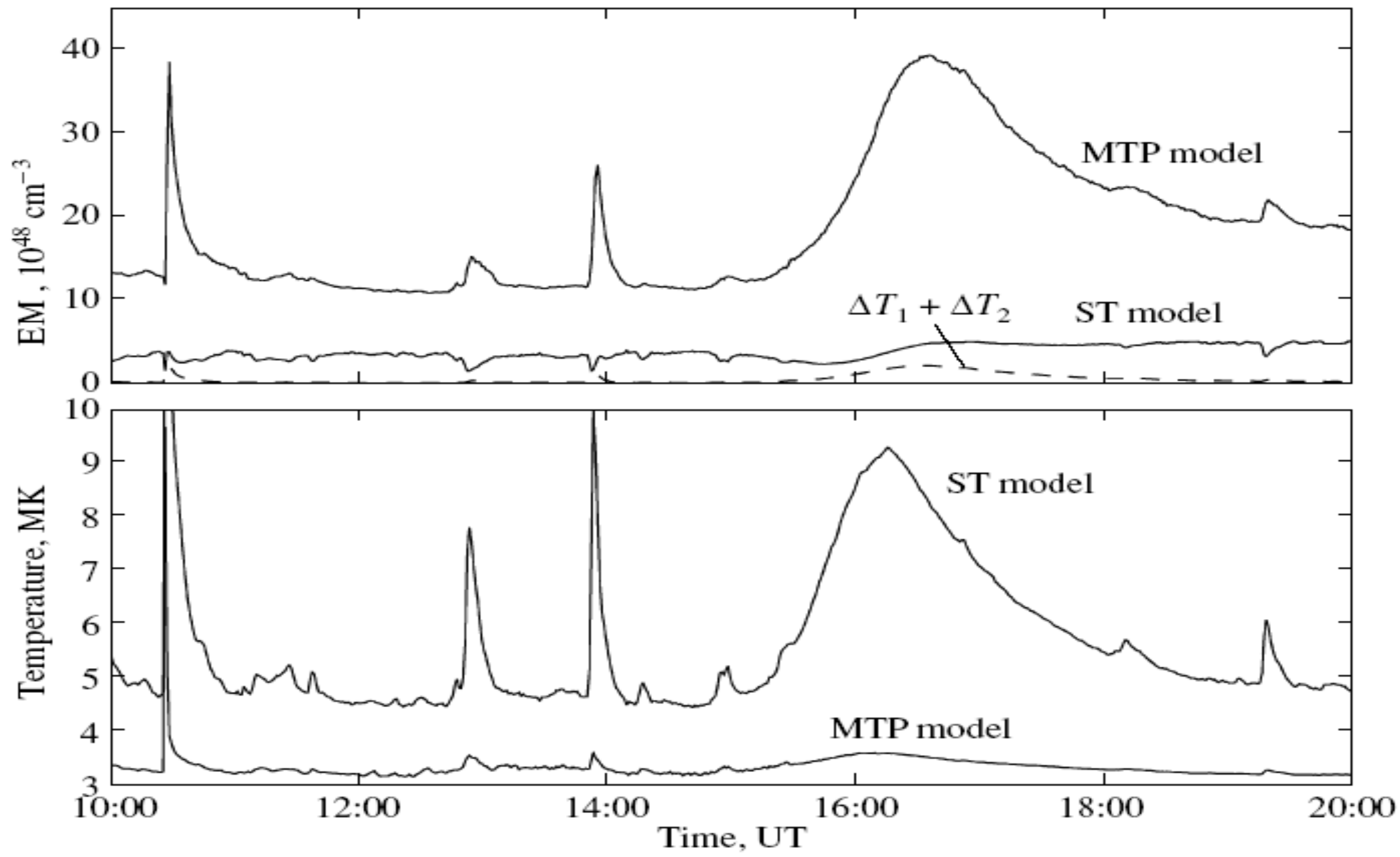


Fig. 4. log DEM (in arbitrary units) versus log T (in K) for active region NOAA 9765, X3.4-class flare (December 28, 2001), and spider (December 28–29, 2001) at the decay phase ($\sim$ 20 h after the maximum).

Comparison of the EM and mean temperature profiles in the MTP and ST models.



$$I_e = C\left\{ \int_{(\tilde{V})} G_e(N_e(\vec{r}); T(\vec{r})) \cdot N_e^2(\vec{r})\, d\vec{r} + G_e(N_i; T_i) N_i^2 \int_{(\bar{V}_i)} d\vec{r} + \right.$$

$$\left. + N_i^2 \int_{(V')} G_e(N_i; T(\vec{r}))\, d\vec{r} + \int_{(V'')} G_e(N(\vec{r}); T_j) N^2(\vec{r})\, d\vec{r} \right\}$$

$$G_e(N;T) \cdot N^2 = C \iint_{(\Delta N; \Delta T)} G_e(N;T) \left\{ \delta(N-\psi(\vec{r})) \delta(T-\phi(\vec{r})) + \delta(N-N_i)\delta(T-T_i) + \right.$$

$$\left. + \delta(N-N_i)\delta(T-\phi(\vec{r})) + \delta(N-\psi(\vec{r}))\delta(T-T_i) \right\} N^2\, dN\, dT$$

$$I_e = C \int G(N;T)\, d^2 M(N,T)$$

$$d^2 M(N,T) = \mu(N,T)\, dN\, dT$$

$$\mu(N,T) = \mu_c + \mu_s \; ; \qquad \mu_s = \bar{\mu}_s + \mu_s' + \mu_s''$$

$$\mu_c = \int \delta(N - \psi(\vec{r})) \cdot \delta(T - \phi(\vec{r})) \cdot N^2 \, d\vec{r}$$

$$\bar{\mu}_s = M_i \, \delta(N - N_i) \, \delta(T - T_i) \; ; \qquad M_i = N_i^2 \, V(N_i ; T_i)$$

$$\mu_s' = M_i \, \delta(N - N_i) \qquad M_i(T) = M(N_i, T) = N_i^2 \int \theta(T - \phi(\vec{r})) \, d\vec{r}$$

$$\mu_s'' = M_j \, \delta(T - T_j) \qquad M_j = M(T_j) = \int_{(V'')} N_j(\vec{r}) \, d\vec{r}$$

$$\mu_c = \int N^2(L) \left| \frac{D(\vec{r})}{D(N, t, L)} \right| dL = \oint \frac{N^2 dL}{|\nabla N| |\nabla T| \cos\theta_{NT}} ;$$

$$t = |\nabla T| \sin\theta_{NT}$$

$$y(T) = \int \mu(N,T)\, dN = \int \delta(T - \phi(\vec{r}))\, N^2(\vec{r})\, d\vec{r} \qquad = \quad \xi(T)$$

$$Z(N) = \int \mu(N,T)\, dT = \int \delta(N - \psi(\vec{r}))\, N^2\, d\vec{r} \qquad = \quad \zeta(N)$$

$$N = f(T):$$

$$\delta(N-\psi(\vec{r}))\,\delta(T-\phi(\vec{r})) = \delta(N-f(T))\,\delta(T-\phi(\vec{r}))$$

$$\psi(\vec{r}) = f(\phi(\vec{r})) = f(T)$$

$$\mu_c(N,T) = \delta(N-f(T)) \int \delta(T-\phi(\vec{r}))\,N^2 d\vec{r}$$

$$Z(N) = \int \mu\, dT = \left(\frac{dN}{dT}\right)^{-1} \cdot \int \delta(T-\phi(\vec{r}))\,N^2(T)\, d\vec{r} = \left(\frac{dN}{dT}\right)^{-1} \cdot y(T)$$