Correction of the Jicamarca Te/Ti ratio problem: Verifying the effect of electron Coulomb collisions on the incoherent scatter spectrum

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The effect of electron coulomb collisions on the incoherent scatter spectrum in the F region at Jicamarca

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Abstract. The fact that the incoherent backscatter spectrum narrows when the radar beam is nearly perpendicular to the magnetic field is well known and has been used at Jicamarca for more than 30 years to measure very accurate line-of-sight velocities. Recently it has become clear that these spectra are narrower than expected. We have explained this effect and also the small change to the spectral shape required at somewhat larger angles to correct the ratio of electron to ion temperature seen in some studies. Coulomb collisions affecting the motion of the electrons are responsible for the additional spectral narrowing. We have carried out very accurate simulations of electron motion resulting in incoherent scatter spectra which are qualitatively similar to spectra resulting from other types of collisions, and to those predicted in an analytic solution for the Coulomb case [*Woodman*, 1967]. However, we found that the spectrum of the velocity time series in the radar line of sight departs significantly from the nearly Lorentzian form expected with simple collisional models. This causes the collisional effects to extend to somewhat shorter scale lengths, or further from perpendicular to the magnetic field than expected. In order to investigate the collisional process more closely, we performed another simulation combining the effects of electron-ion collisions and a simple friction model (Langevin equation) in an adjustable combination. This one showed that the effect of electron-ion collisions alone would result in collisional effects extending several degrees farther from perpendicular to the field than when both kinds of collisions are included. Collisions affecting the speed of the electrons tend to limit the size of the effect at larger angles from perpendicular. Thus the effect of these collisions on the incoherent scatter spectrum cannot be accurately predicted from simple models but depends on the detailed physics of the collisions.

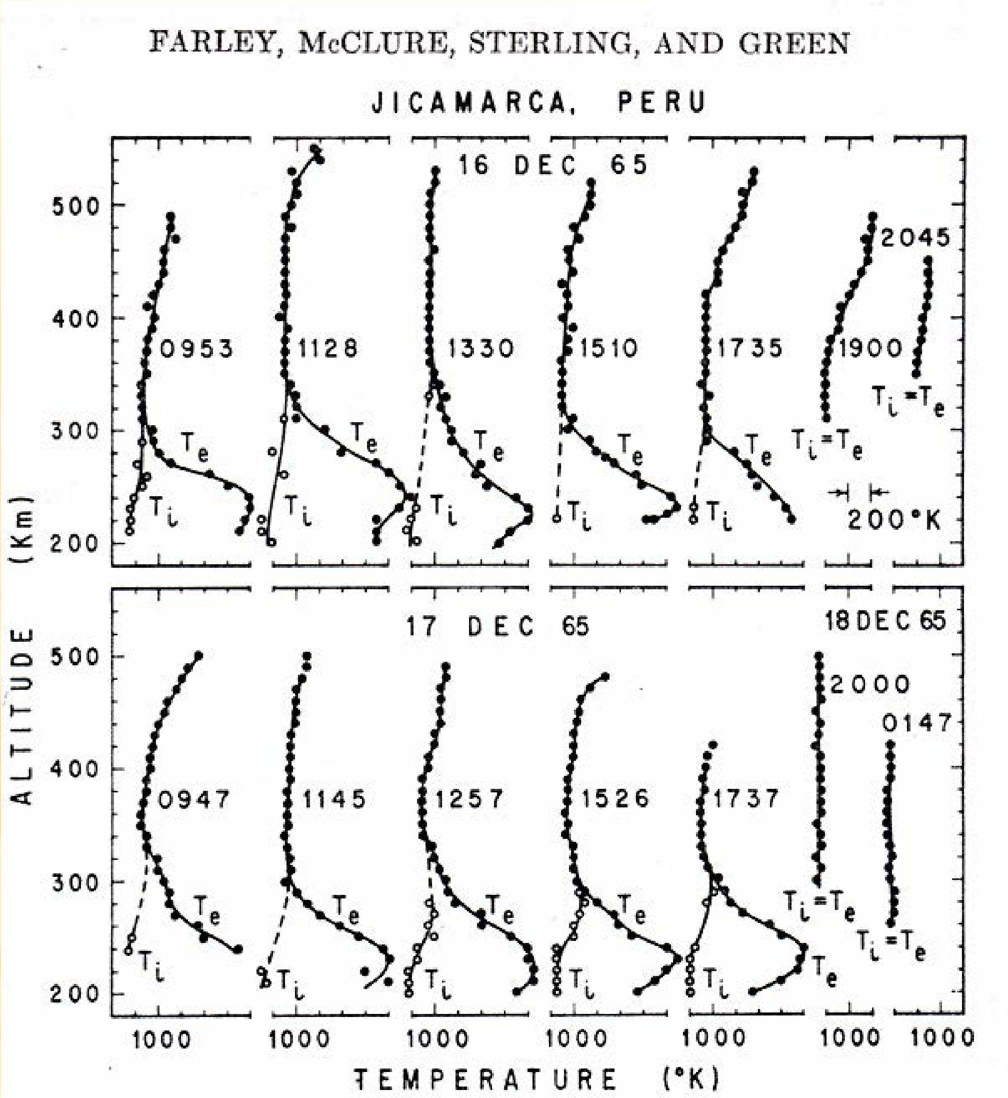
1. Introduction

Recent efforts to derive temperatures from incoherent backscatter spectra collected at the Jicamarca Radio Observatory over part of the range of pointing angles to the magnetic field have encountered difficulties in obtaining realistic values. Previous studies have pointed out an apparent discrepancy between electron temperatures measured at Jicamarca and using probes on satellites, suggesting that the radar temperatures are somewhat low [e.g., *Hanson et al.*, 1969; *McClure et al.*, 1973]. More recently, it has been determined that it is necessary to point at angles of at least 4° to obtain the higher "reasonable" temperatures [e.g., *Pingree*, 1990; *Aponte*, 1998; *D. Hysell*, private communication, 1996; *E. Kudeki*, private communication, 1997]. *Aponte* [1998] presented autocorrelation functions (ACFs) taken at several angles to the field in his

Topics

1. Te/Ti ratio problem
2. Coulomb Collision Theory
3. F region results
4. Topside measurements

1960s Jicamarca Temperatures



Upper heights from LSF assuming Te=Ti

Lower heights from zero crossing and first minimum

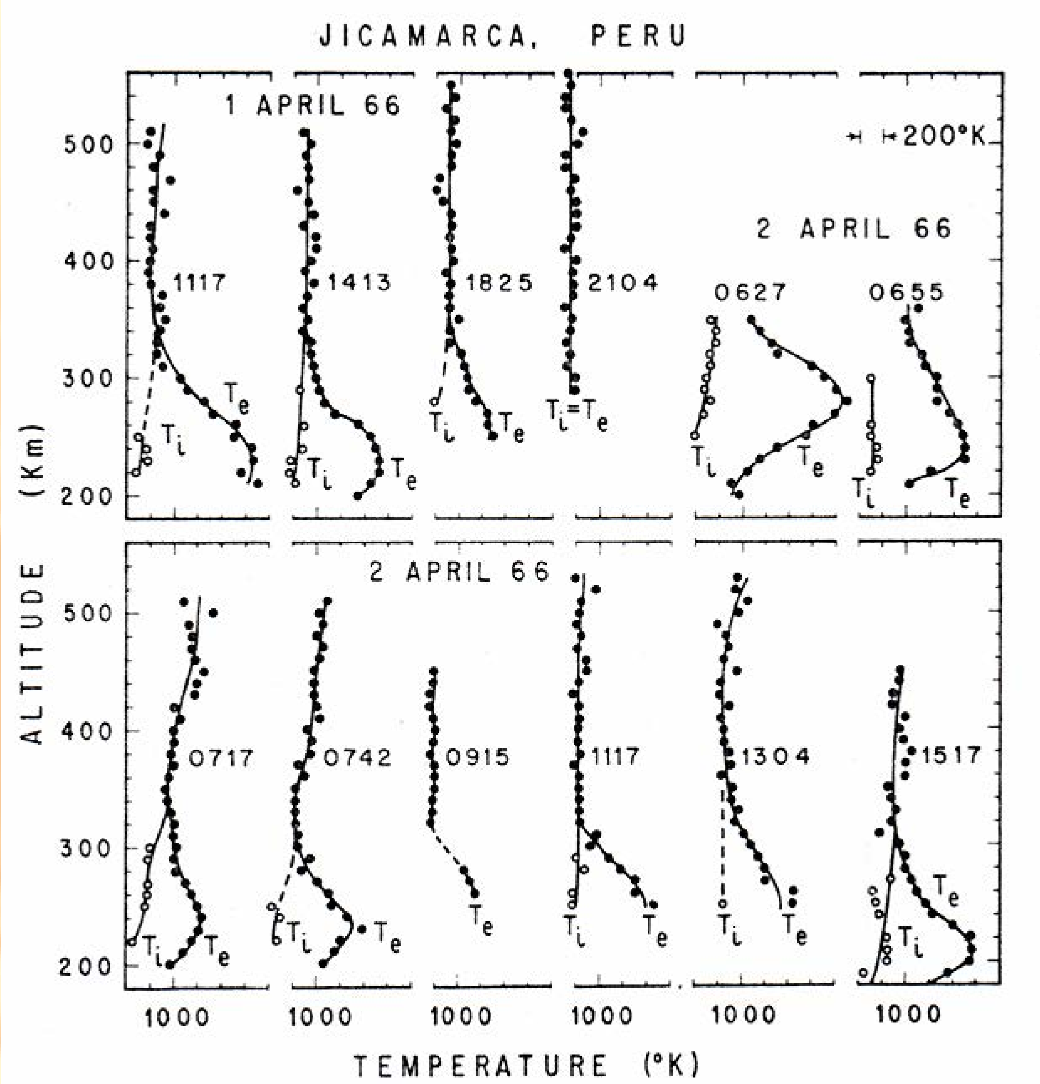


Fig. 6. A series of equinox profiles of the electron and ion temperature.

Farley et al. [1967]

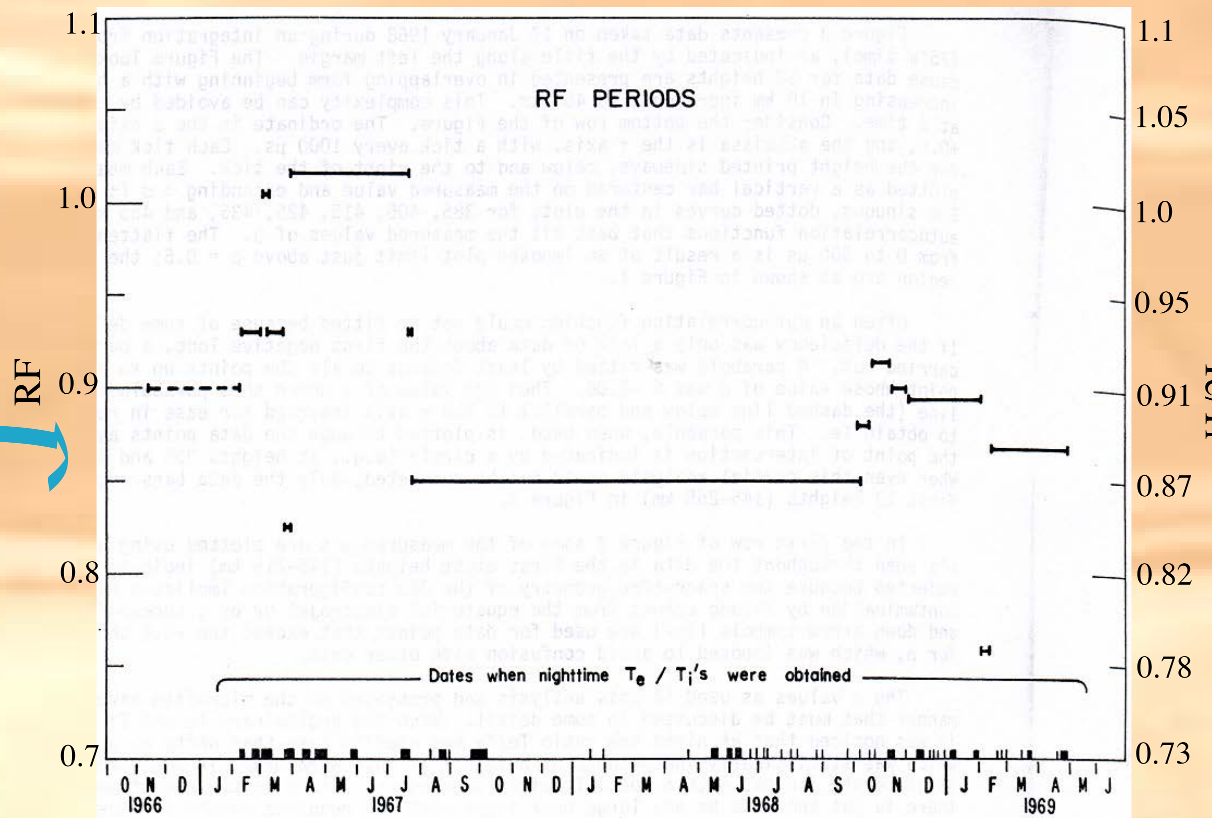
Clark et al. Report [1976]

1966-1969 Jicamarca data reprocessed via LSF

Found that " at night the ratio Te/Ti was usually less than unity by a significant factor ..."

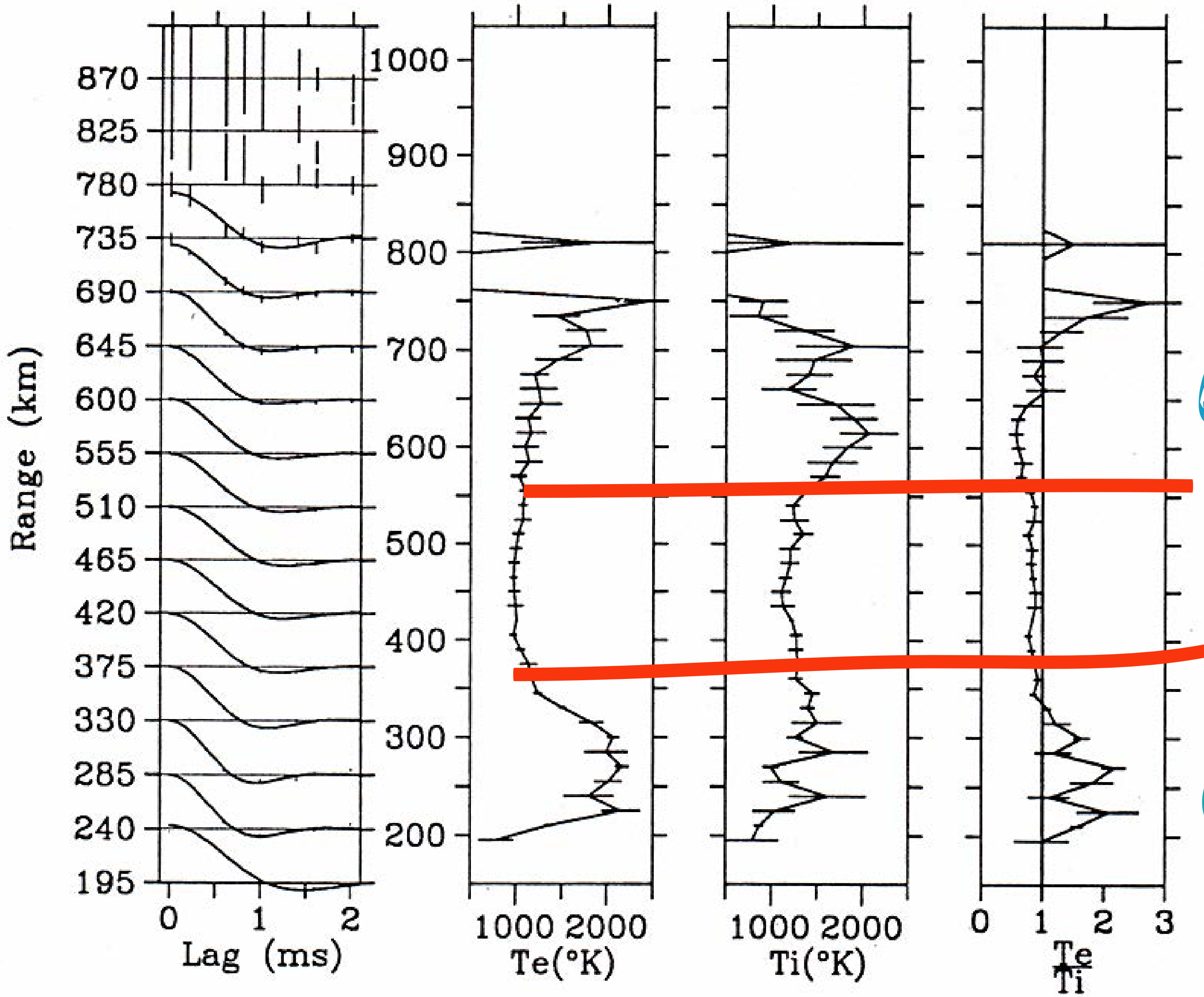
Nighttime median Te/Ti vs. Time

RF (□ factor) to correct ACFs so that Te/Ti=1 at night



Jicamarca June 16, 1988 on-axis

Pingree [1990]

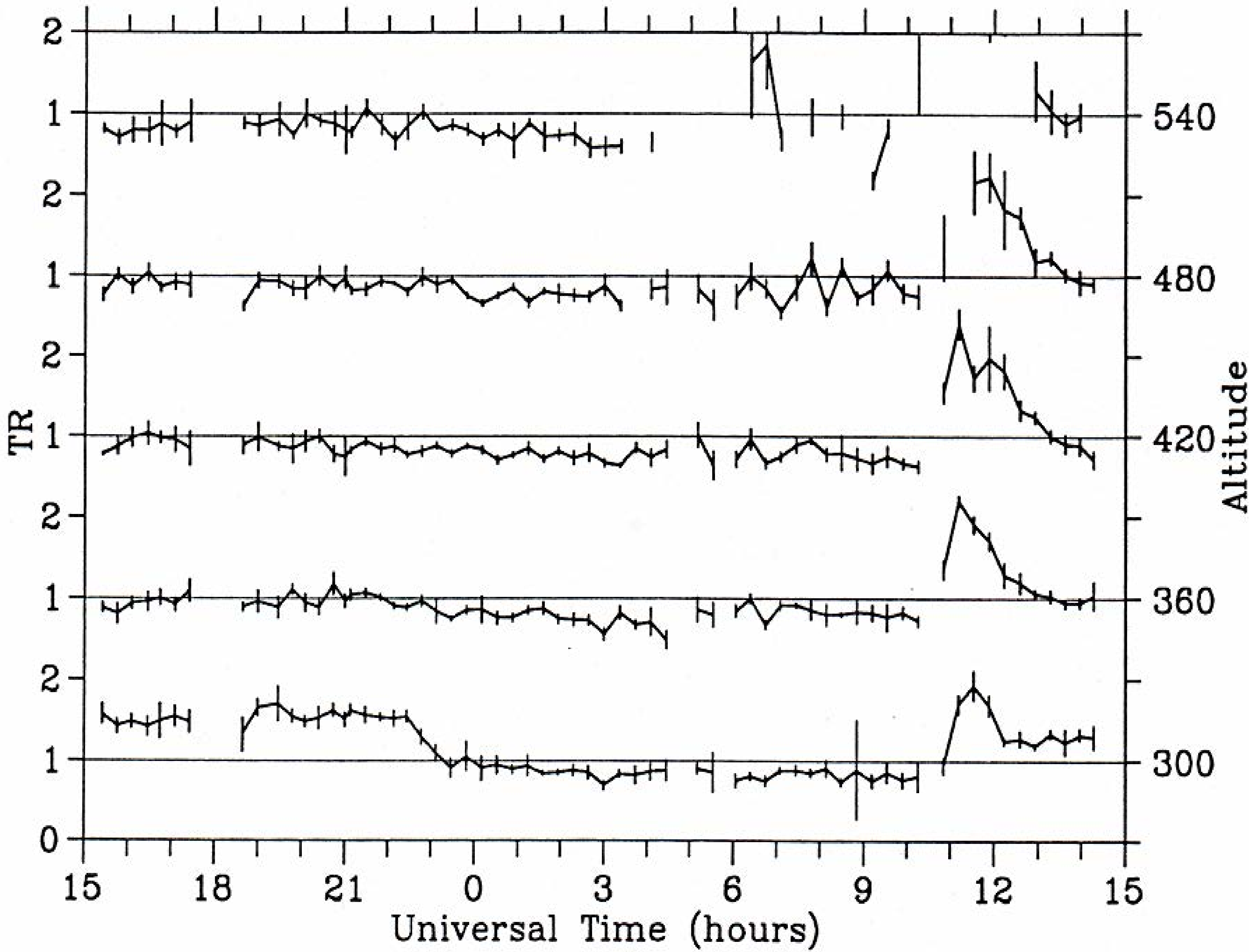


Lower S/N
More H+

O+, Good S/N, Small
Ejet effects -
No CC theory leads
to Te/Ti<1 fits

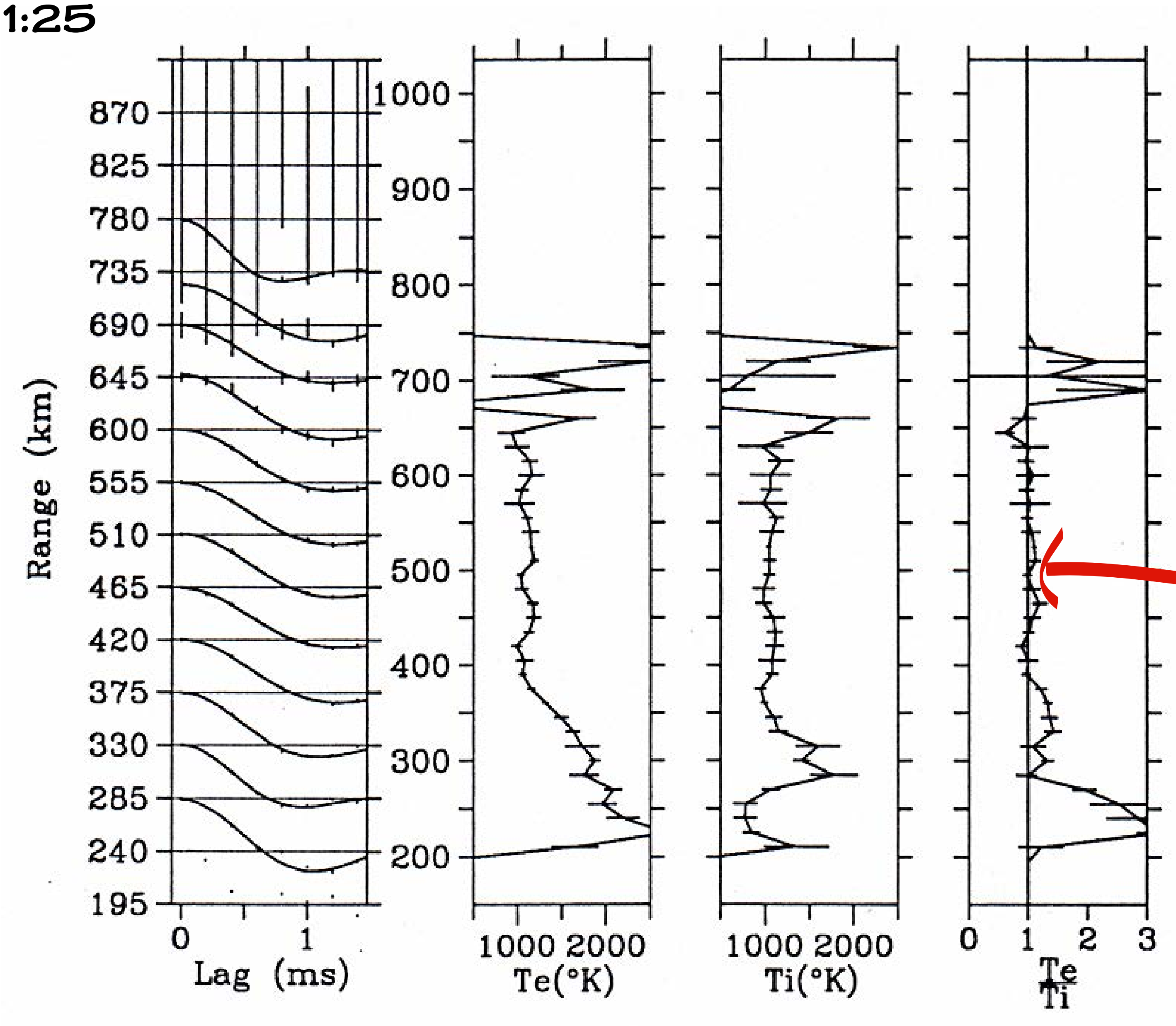
Te/Ti > 1 Region
Most affected
by coherent
echoes (E-Jet,
150 km echo)

Jicamarca Te/Ti June 16-17, 1988 on-axis



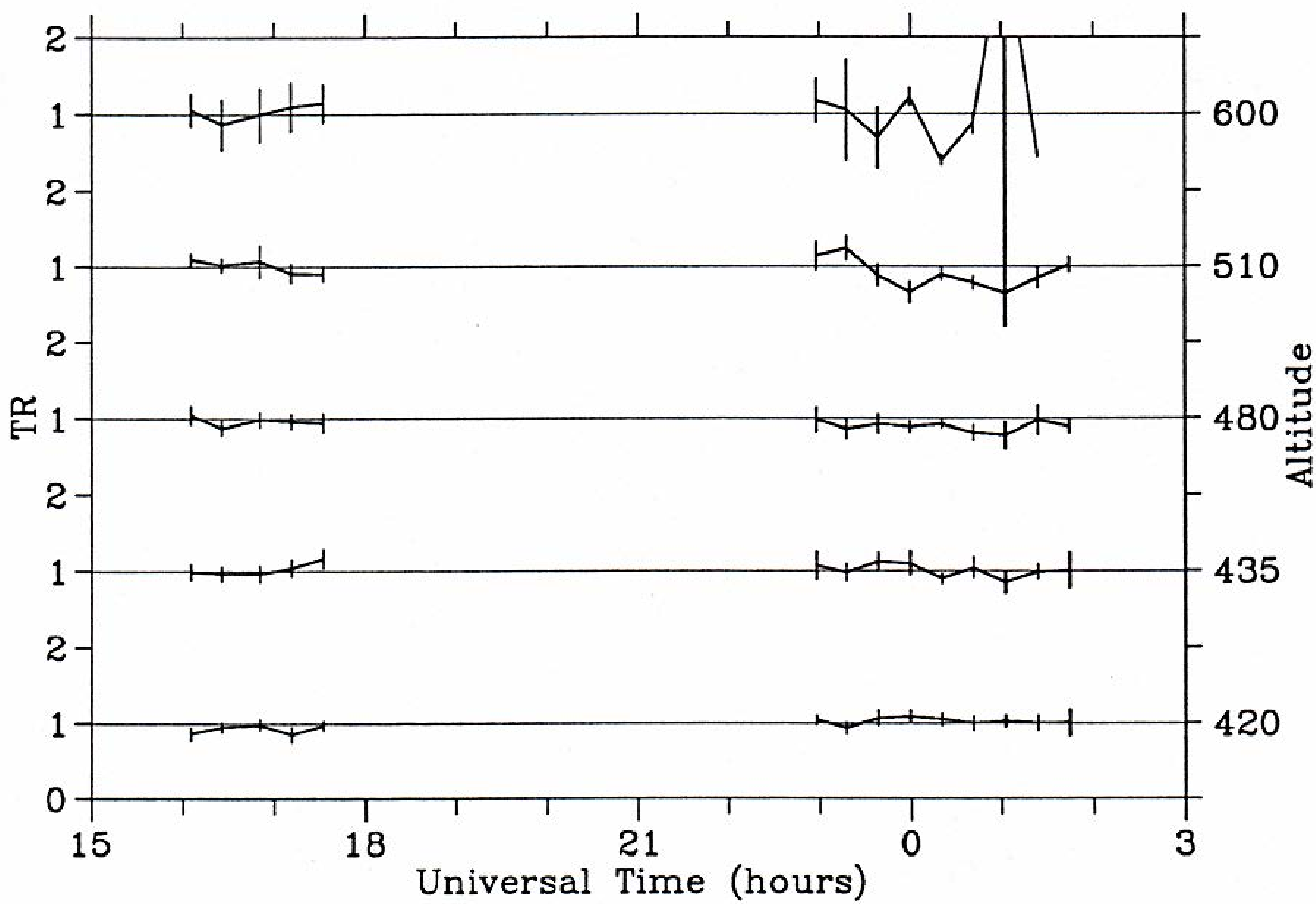
Jicamarca July 3, 1988 - 6 degrees

11:05-11:25



Te /Ti ≃ 1 in the F region As expected at the equator.

Jicamarca Te/Ti July 3-4, 1988 - 6 degrees



Pingree [1990] Findings on Te<Ti problem

"Temperature measurements made using two different antenna positions (3 and 6) are not consistent."

(Te<Ti at 3 but not at 6)

"An exhaustive study of potential systematic experimental errors fail to provide an explanation for the inconsistency."

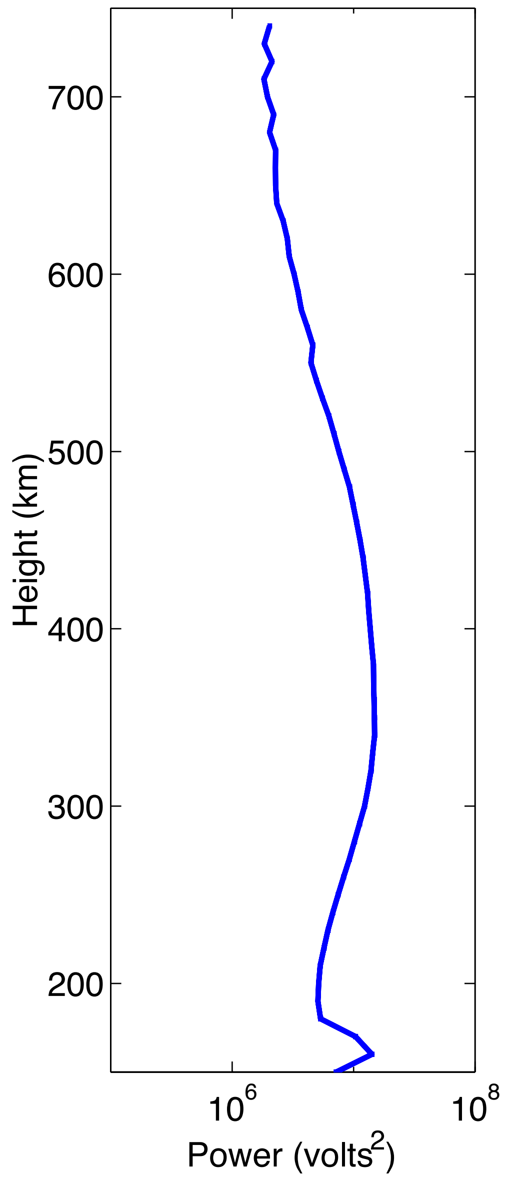
(Over 70 pages of his thesis dedicated to sys. errors)

"There are thus only two conclusions possible:(1) there is still an unknown systematic error ... or (2) there is an error in the derivation of the incoherent scatter spectrum ... negligible except within three degrees of perpendicularity."

Summary of Coulomb Collision Theory

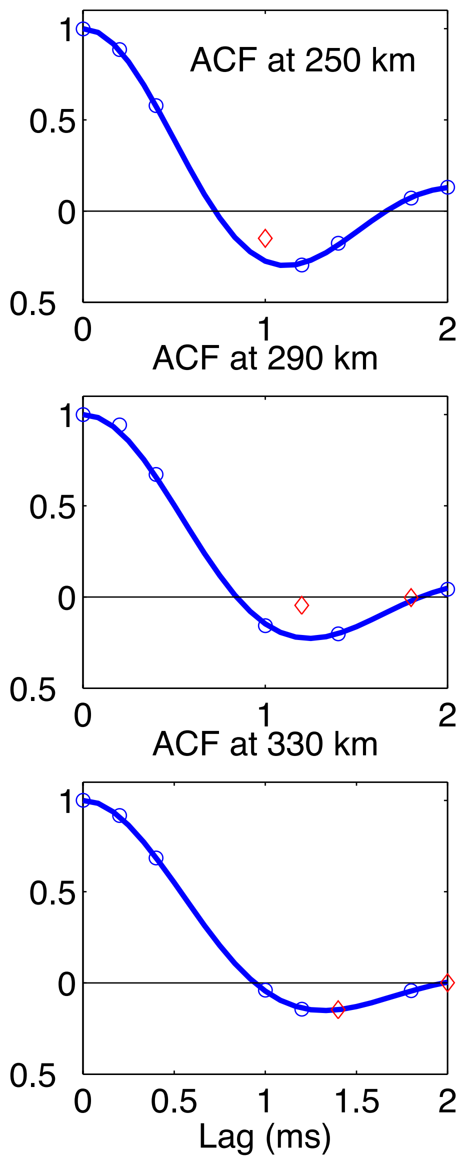
Power

<V^2>



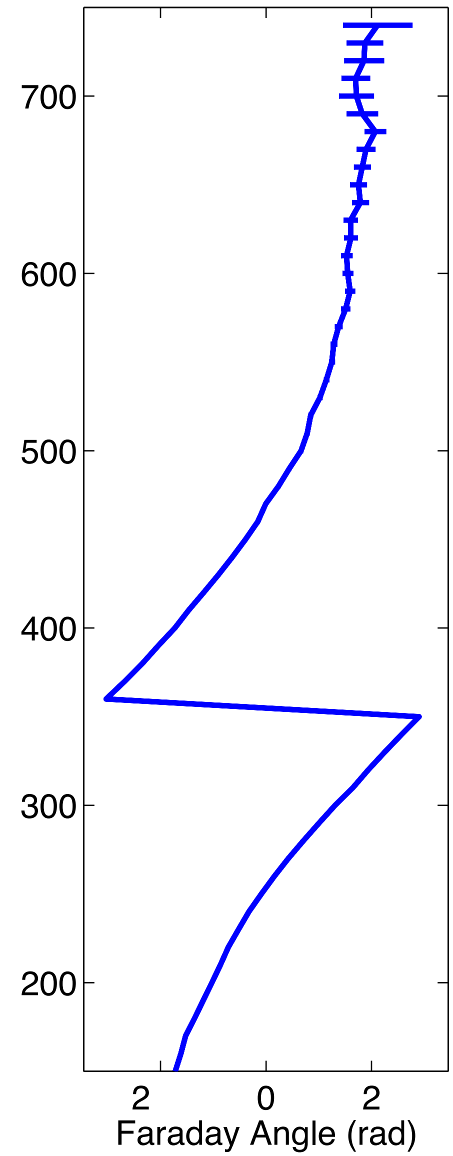
Autocorrelation Function

<V(t)V*(t+□)>



Faraday Angle

<□R□□L>

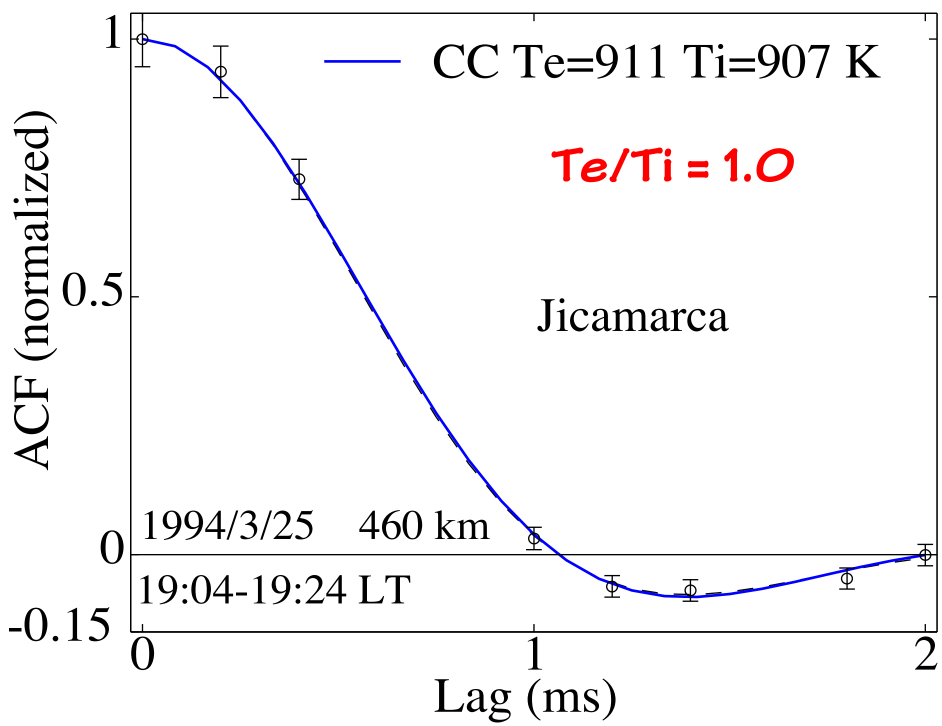


Only at Jicamarca

Requires 2 Polarizations

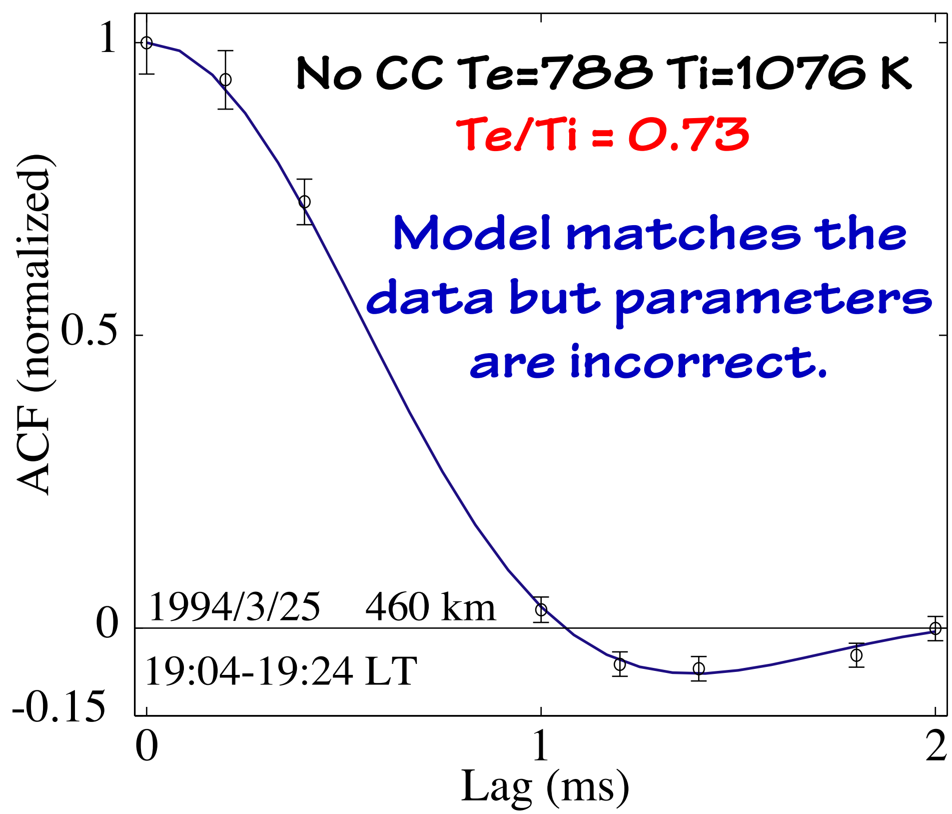
Least squares fitting of Autocorrelation Function

CC Theory



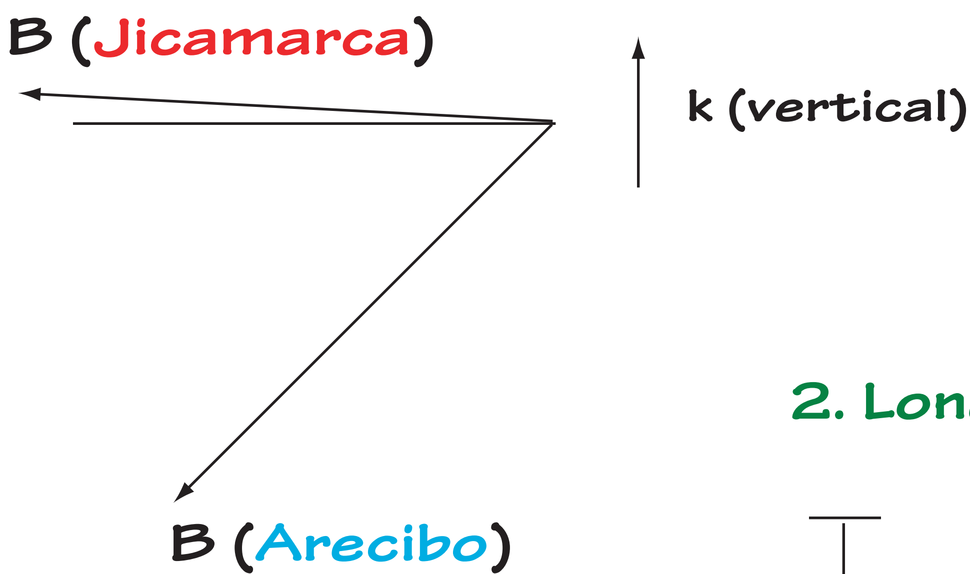
$$\chi^2 = \sum_j \frac{[\rho(\tau_j) - \hat{\rho}(\tau_j, T_e, T_i, N_e, ...)]^2}{\sigma_j^2}$$

Regular Theory

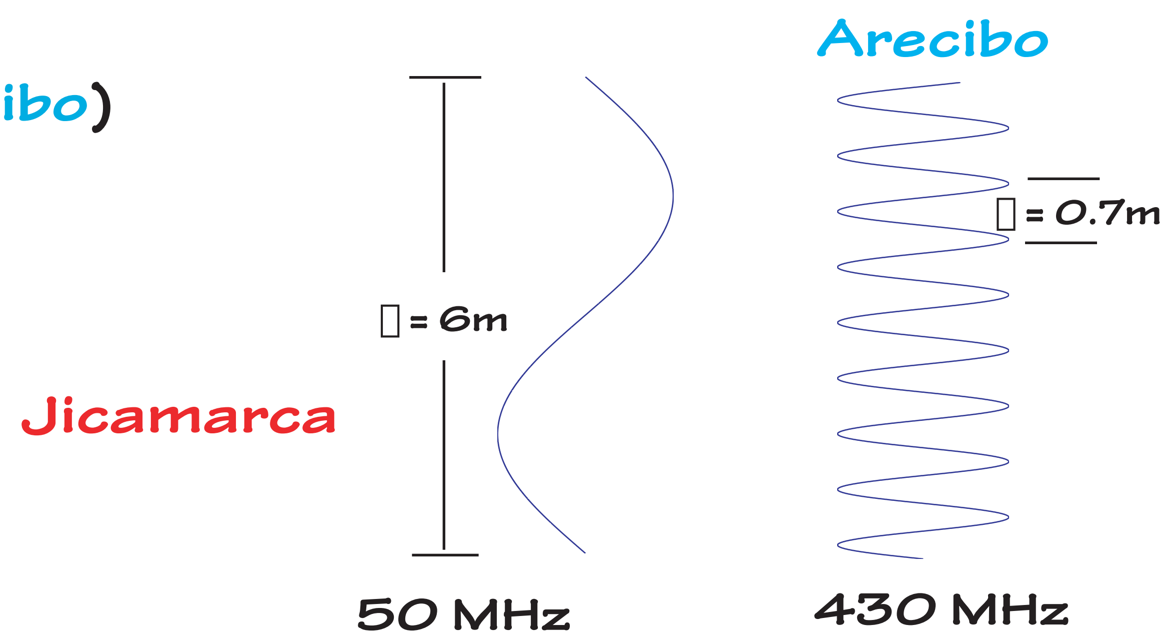


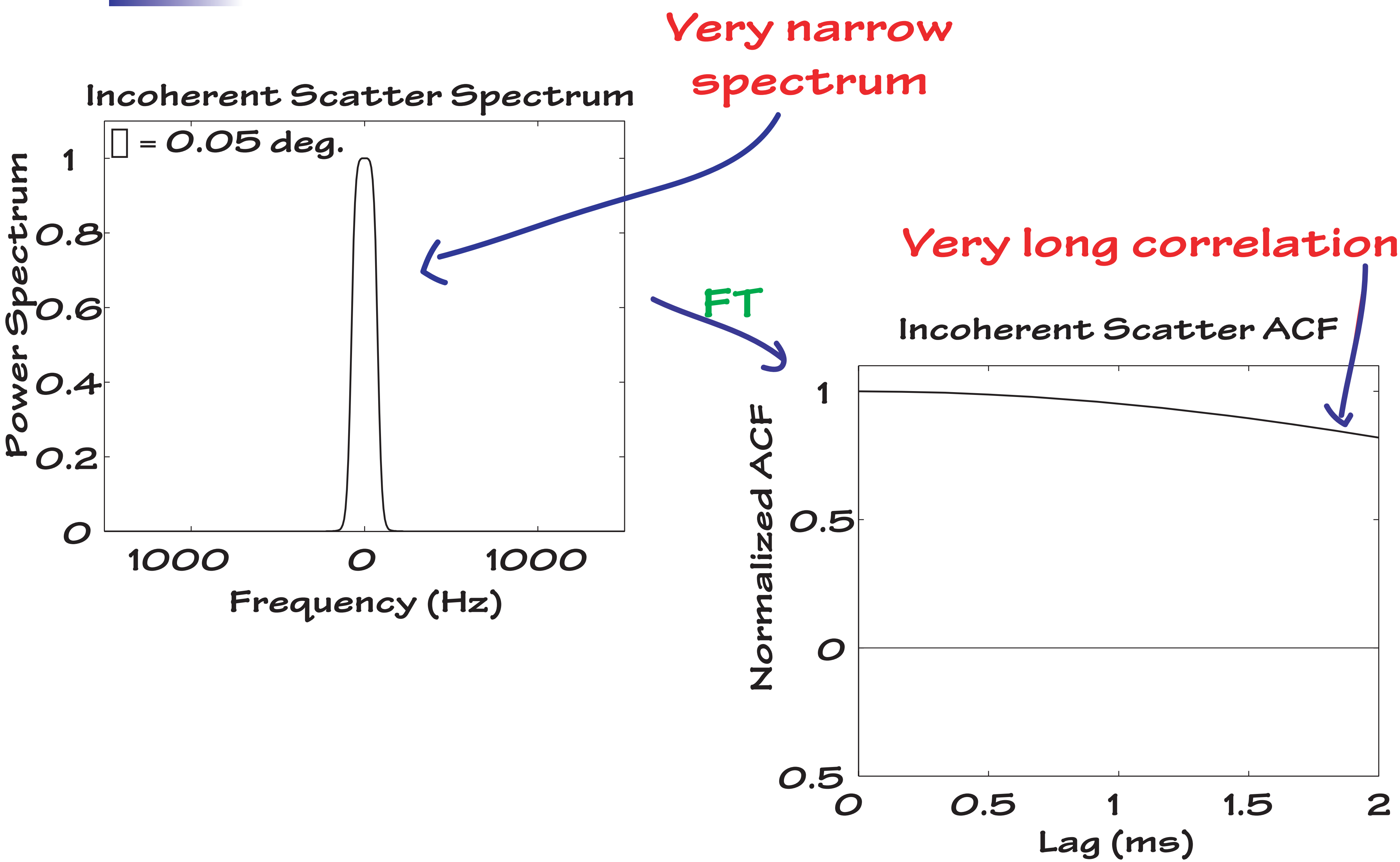
What makes Jicamarca different than other ISRs?

1. Horizontal Magnetic Field



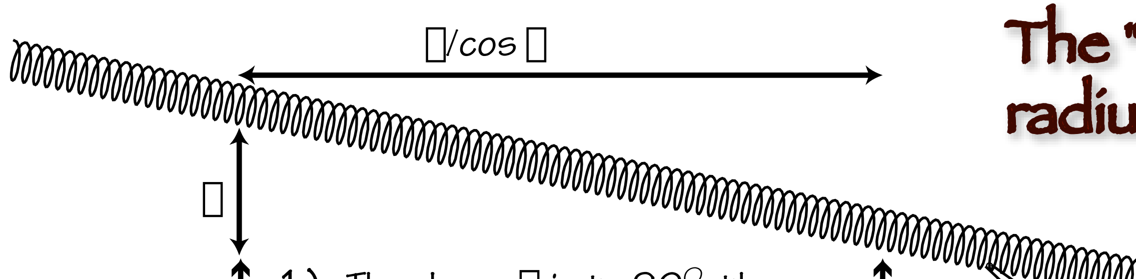
2. Longer Wavelength





Very narrow spectrum
Incoherent Scatter Spectrum
□ = 0.05 deg.
Power Spectrum
1
0.8
0.6
0.4
0.2
0
1000
0
1000
Frequency (Hz)
FT
Very long correlation
Incoherent Scatter ACF
Normalized ACF
1
0.5
0
0.5
0
0.5
1
1.5
2
Lag (ms)

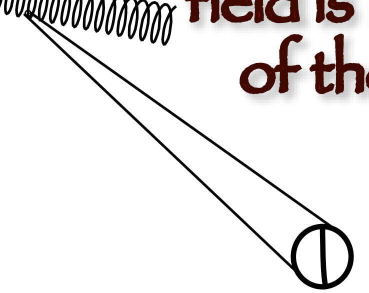
The "strong field approximation" (gyro radius small compared to the wavelength) means changing the angle to the field is like changing the magnitude of the k vector with no field.



1.) The closer [illegible] is to 90°, the farther the electron must move to affect the phase of the radar signal.

Conclusion: collisions affect the spectrum close to perpendicularity since they require a similar distance to affect the phase as does uniform motion.

Rays from radar (assumed parallel in the far field)



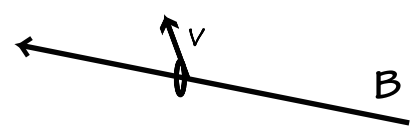
2.) The small size of the Debye sphere means that the electron has very small curvature on that scale.

Conclusion: the collision process does not know about the magnetic field.

3.) If the gyroradius is small compared to a radar wavelength, then the gyromotion does not affect the phase of the radar signal.

Conclusion: The electron effectively moves like a "bead on a wire". Only the velocity component along the field matters. The random nature of this component determines the spectrum.

4.) The direction of the velocity vector is an axs of symmetry for the Coulomb collisional force. Since the gyro-motion causes the velocity vector to rotate about the direction of B, the component of the force in that direction is unchanged by the gyro-motion.



Conclusion: The magnetic field does not change the component of motion that affects the radar signal phase, and thus can be ignored except for setting the scale of the radar signal phase change as described above.

Incoherent Scatter Spectrum

Swartz and Farley [1979]

$$\sigma(\omega_0+\omega)d\omega = \frac{N r_e^2 d\omega}{\pi} \frac{\left(|y_e|^2 \frac{\sum_j n_j Re(y_j)}{\omega - \mathbf{k}\cdot\mathbf{v}_{dj}} + |\sum_j \mu_j y_j + i h^2 k^2|^2 \frac{Re(y_e)}{\omega - \mathbf{k}\cdot\mathbf{v}_{de}}\right)}{\left(|y_e + \sum_j \mu_j y_j + i h^2 k^2|^2\right)}$$

Physics of the problem in the plasma response functions y_j and y_e

y_e -> electron admittance function
Quantity that must be modified to include effect of electron Coulomb collisions

Looking at y_e in more detail

$y_e = i + \square J_e(\square)$

□ ->normalized frequency

J_e -> a complex function of frequency and wave number □(□,k)

Collisionless J_e vs. J_e with Electron Coulomb Collisions

1) Collisionless (high B field or small gyroradius)

$$J(\theta) = \int_0^\infty e^{-i\theta t' - 0.25 t'^2 \cos^2 \alpha} dt'$$

Fourier Transform of a Gaussian

2) Electron Coulomb Collisions

No analytic solution!

Two important things about J_e :
1) It can be computed from $Re(J_e)$
2)Physical meaning of $Re(J_e)$:
Single particle electron spectrum

Single Particle Spectrum

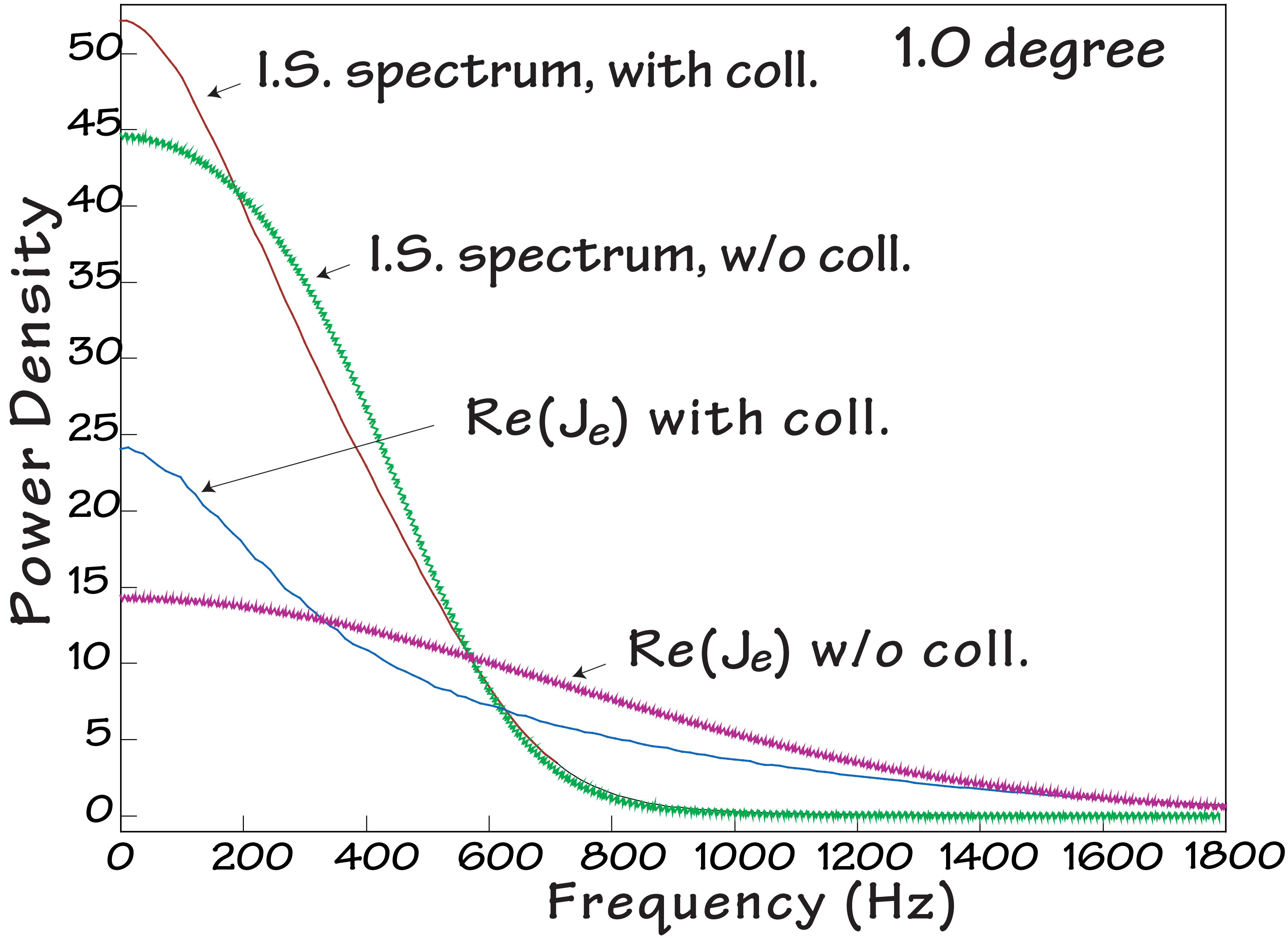
Hagfors and Brockelman [1971]

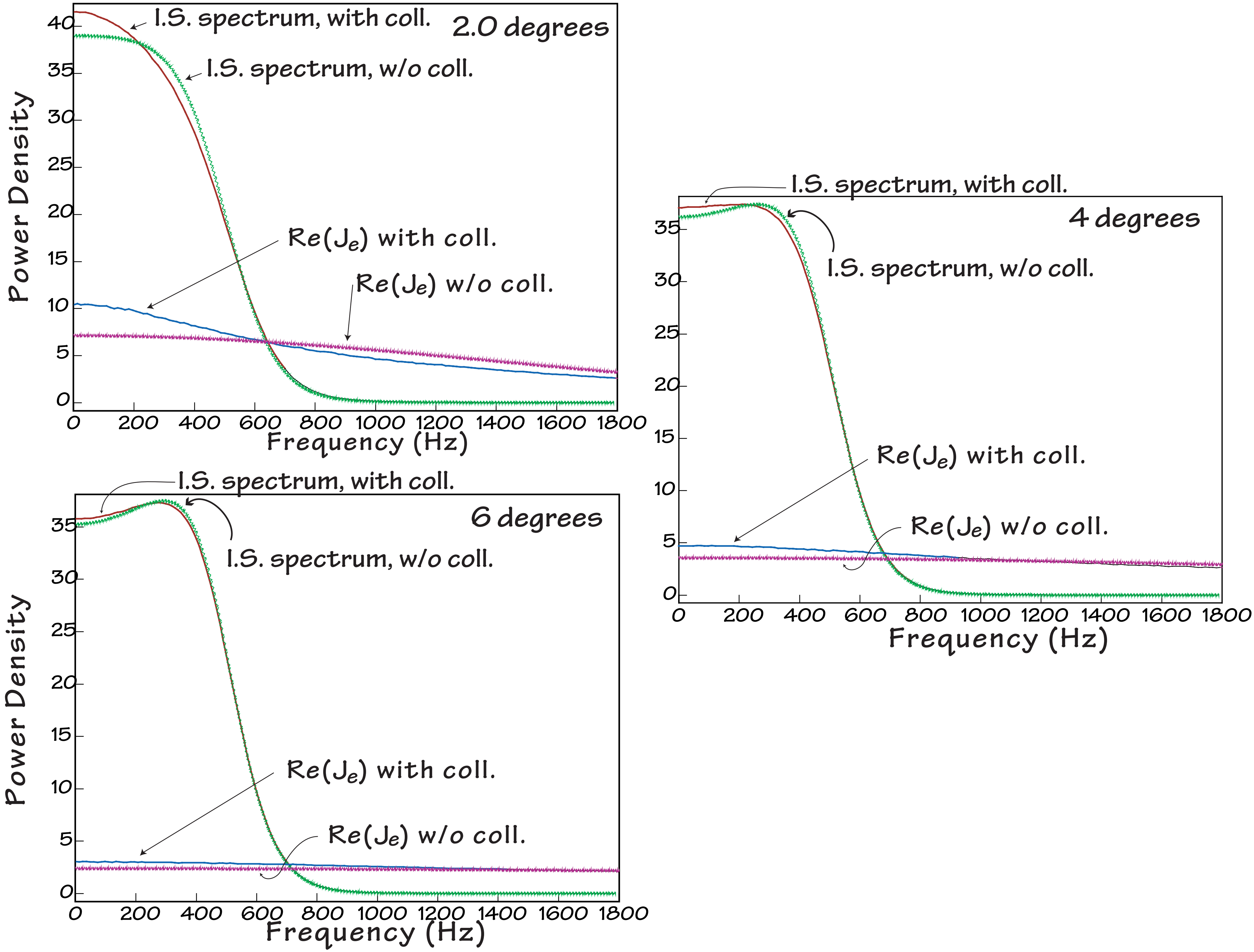
Important Result: single particle spectrum can be computed from the location of a particle in space as a function of time.

Because of this result:

A computer simulation can be used to model the single particle spectrum of an electron affected by Coulomb collisions.

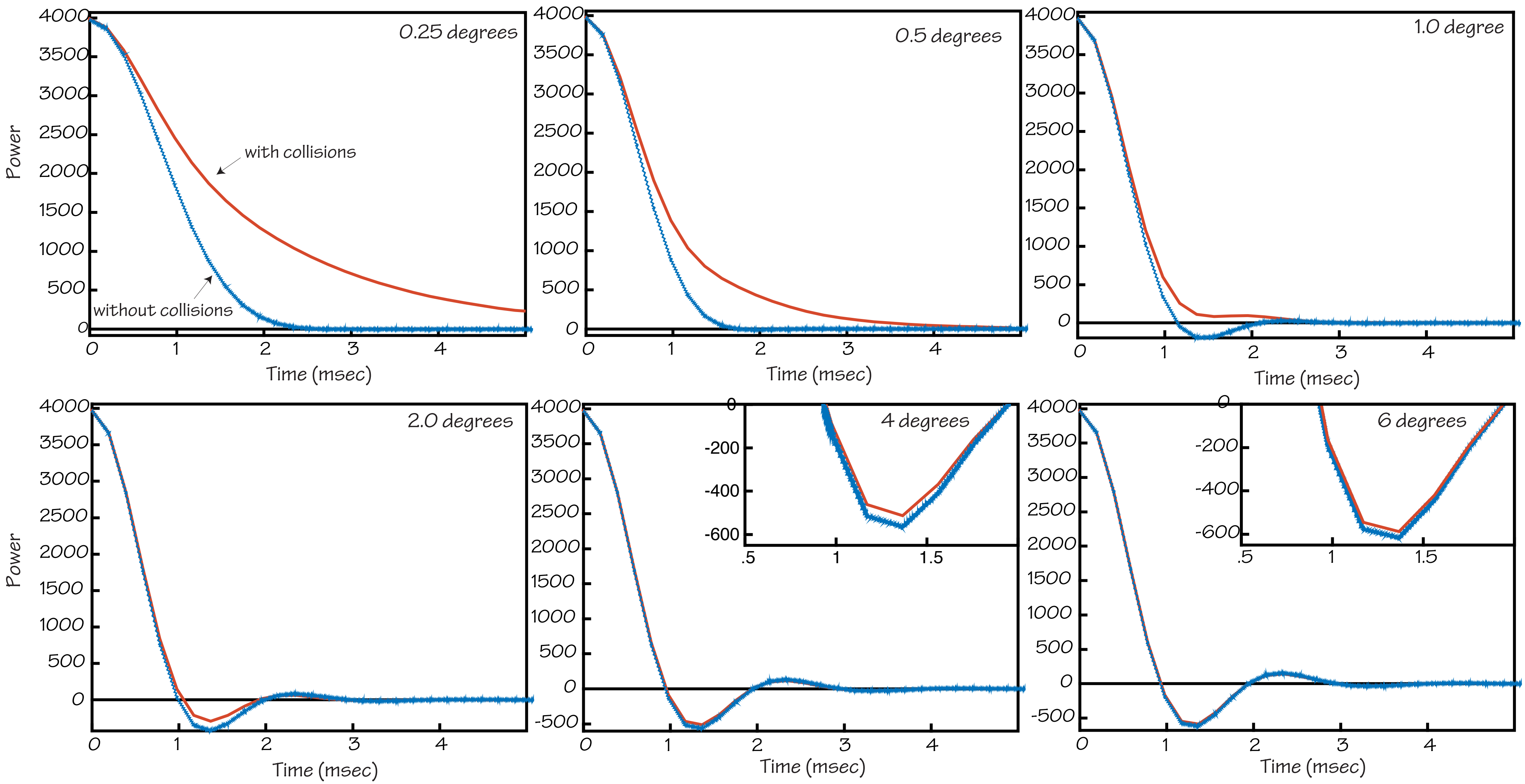
Re (J_e) and I.S. Spectrum



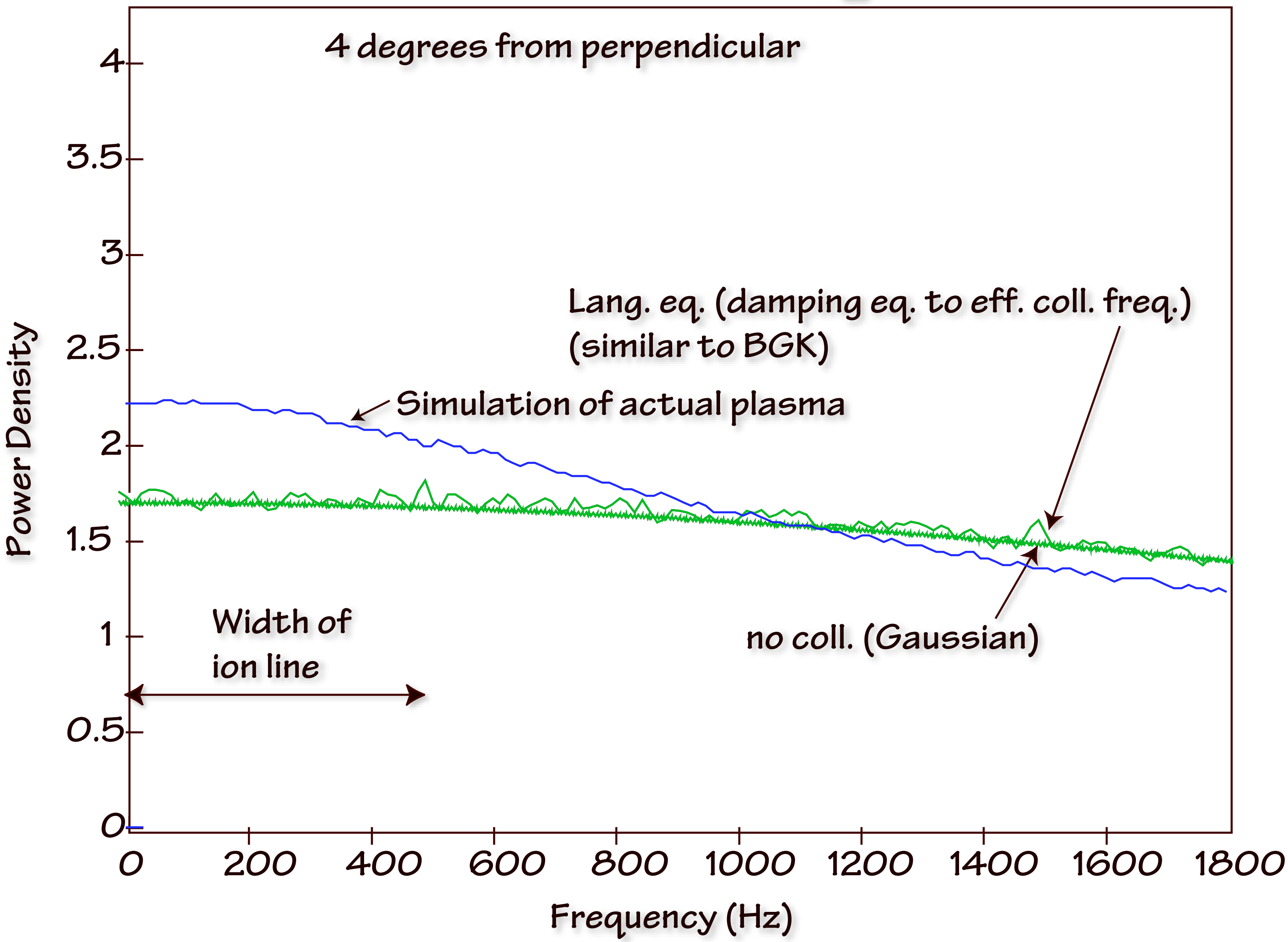


I.S. spectrum, with coll.
2.0 degrees
I.S. spectrum, w/o coll.
Re(J_e) with coll.
Re(J_e) w/o coll.
Power Density
Frequency (Hz)
0
5
10
15
20
25
30
35
40
200
400
600
800
1000
1200
1400
1600
1800
I.S. spectrum, with coll.
4 degrees
I.S. spectrum, w/o coll.
Re(J_e) with coll.
Re(J_e) w/o coll.
Frequency (Hz)
I.S. spectrum, with coll.
6 degrees
I.S. spectrum, w/o coll.
Re(J_e) with coll.
Re(J_e) w/o coll.
Power Density
Frequency (Hz)

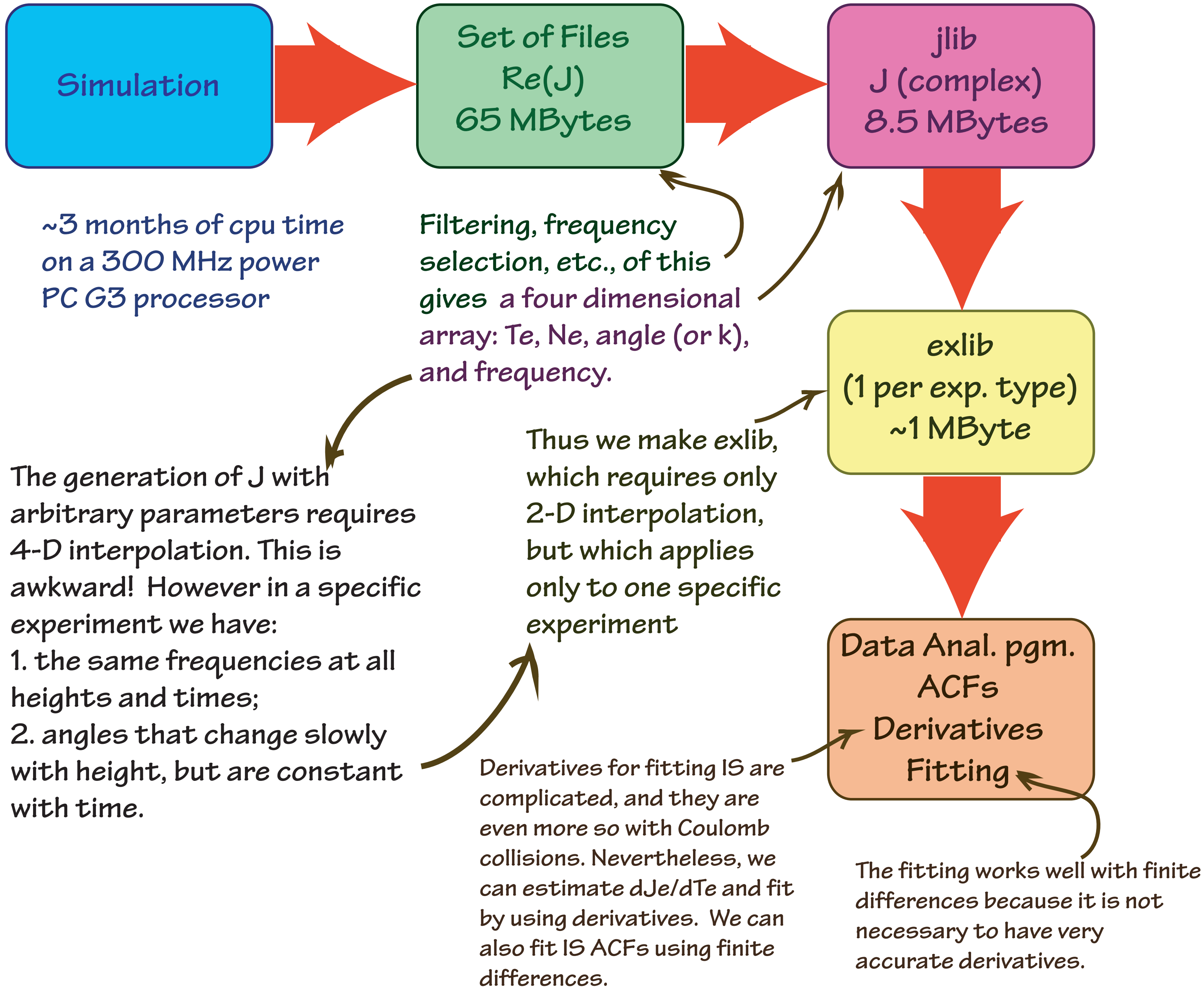
ACFs at Various Angles with and without Collisions



Single Particle Spectra* with No Colllisions, Langevin'S Equation, and the Full Simulation
*same as Re{J_e}



How to Use the Simulation Results for Analyzing Data



Modifications to Incoherent Scatter Spectrum

Theory without Coulomb Collisions

$$y_{eR}(\theta) = (1 - T_e C_B)\frac{\theta}{cos\alpha} Z_I\left(\frac{\theta}{cos\alpha}\right)$$

$$y_{eI}(\theta) = 1 + (1 - T_e C_B)\frac{\theta}{cos\alpha} Z_R\left(\frac{\theta}{cos\alpha}\right)$$

Swartz [1978]
High B field,
low frequency
approximation

ye - only quantity that needs to be changed (plus its derivative dye/dTe)

Theory with Coulomb Collisions

$$y_{eR} = \omega J_{eR}(f, \alpha, N_e, T_e)$$

Sulzer and Gonzalez [1999]

$$y_{eI} = 1 + \omega J_{eI}(f, \alpha, N_e, T_e)$$

$$\frac{\partial y_{eR}}{\partial T_e} = \omega \frac{\partial J_{eR}}{\partial Te}$$

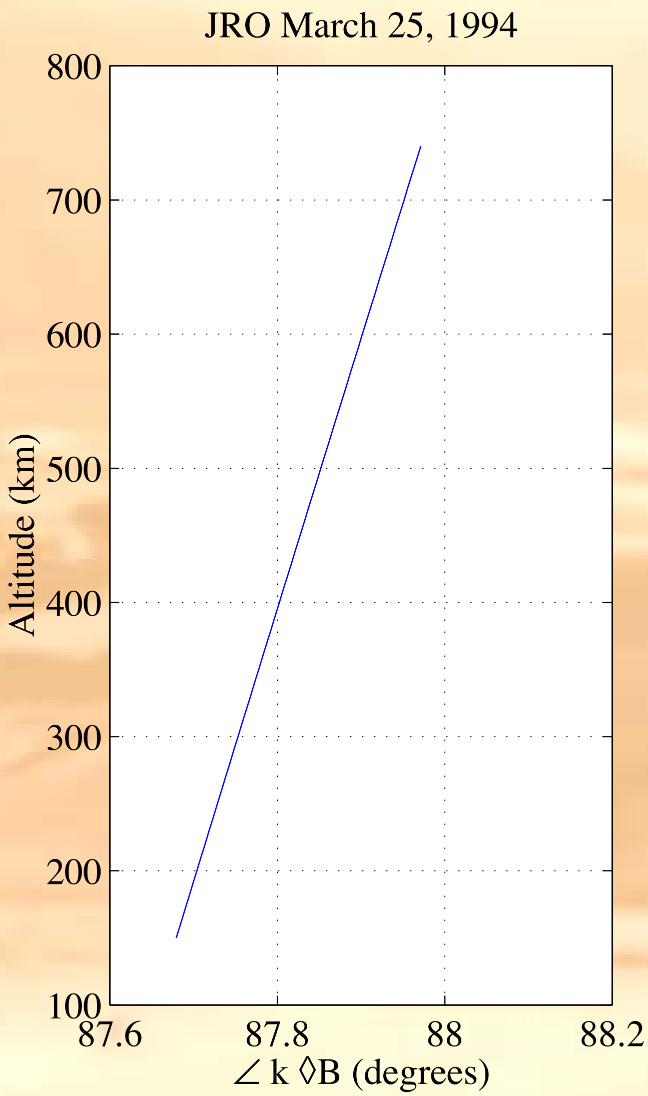
Estimated from Je interpolation

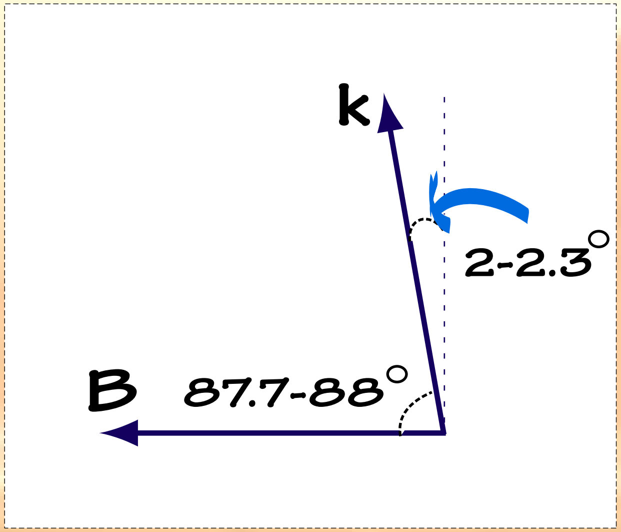
$$\frac{\partial y_{eI}}{\partial T_e} = \omega \frac{\partial J_{eI}}{\partial Te}$$

Je library from simulation

F Region Temperatures

on-axis

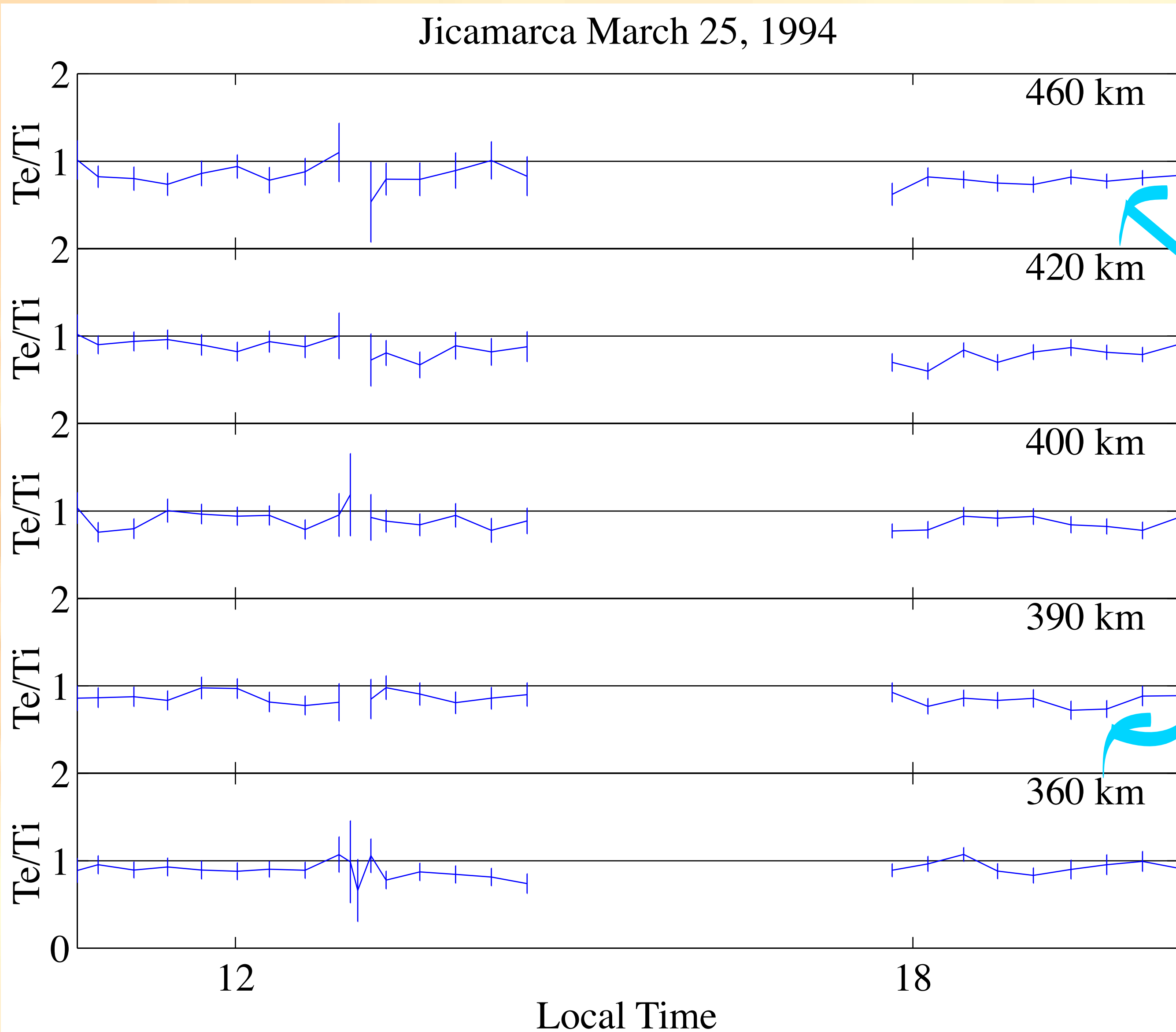




Closer now to 2° from perpendicular to B

March 25, 1994 - Fits without Coulomb Collisions

on-axis

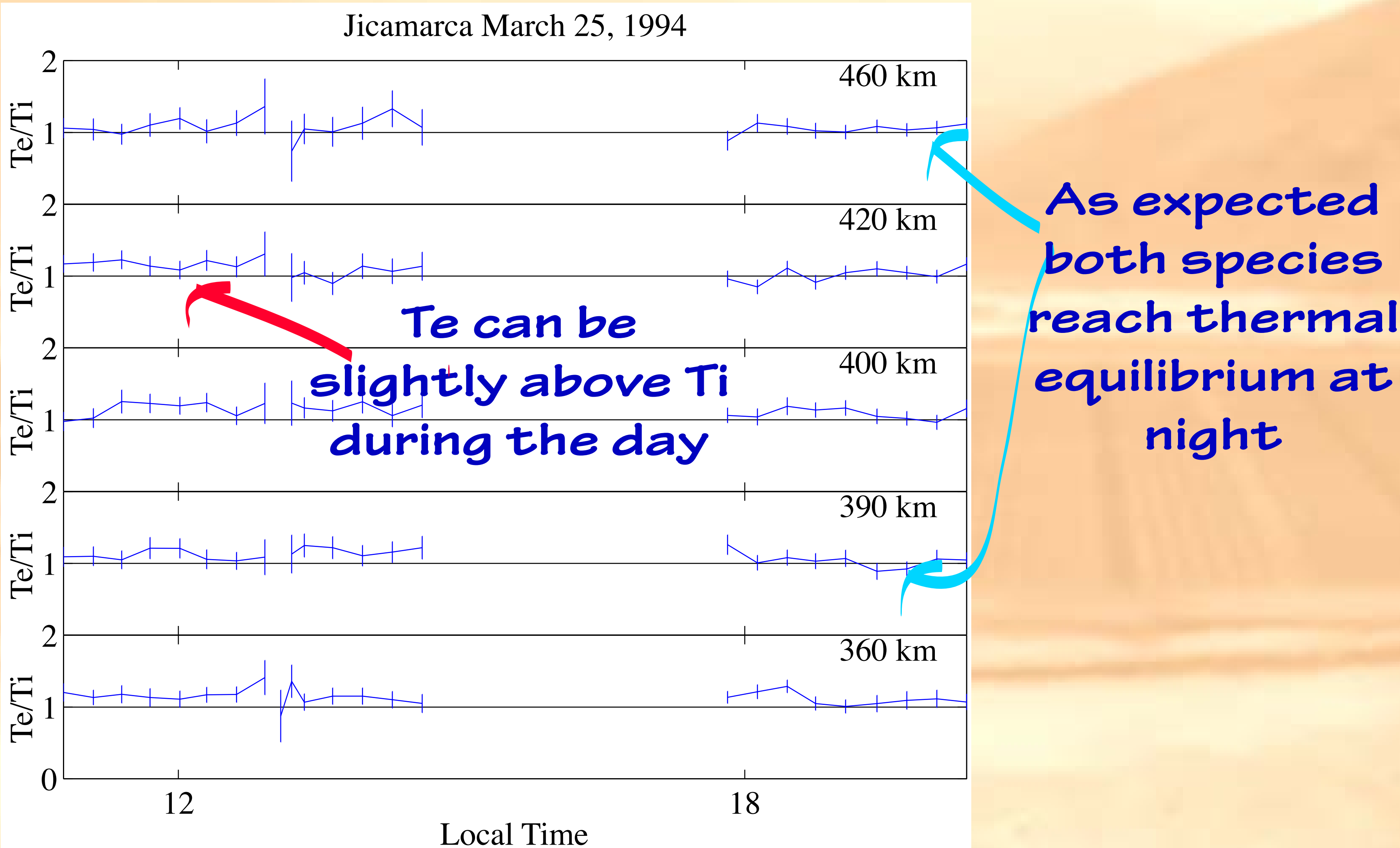


Te lower than Ti especially at night

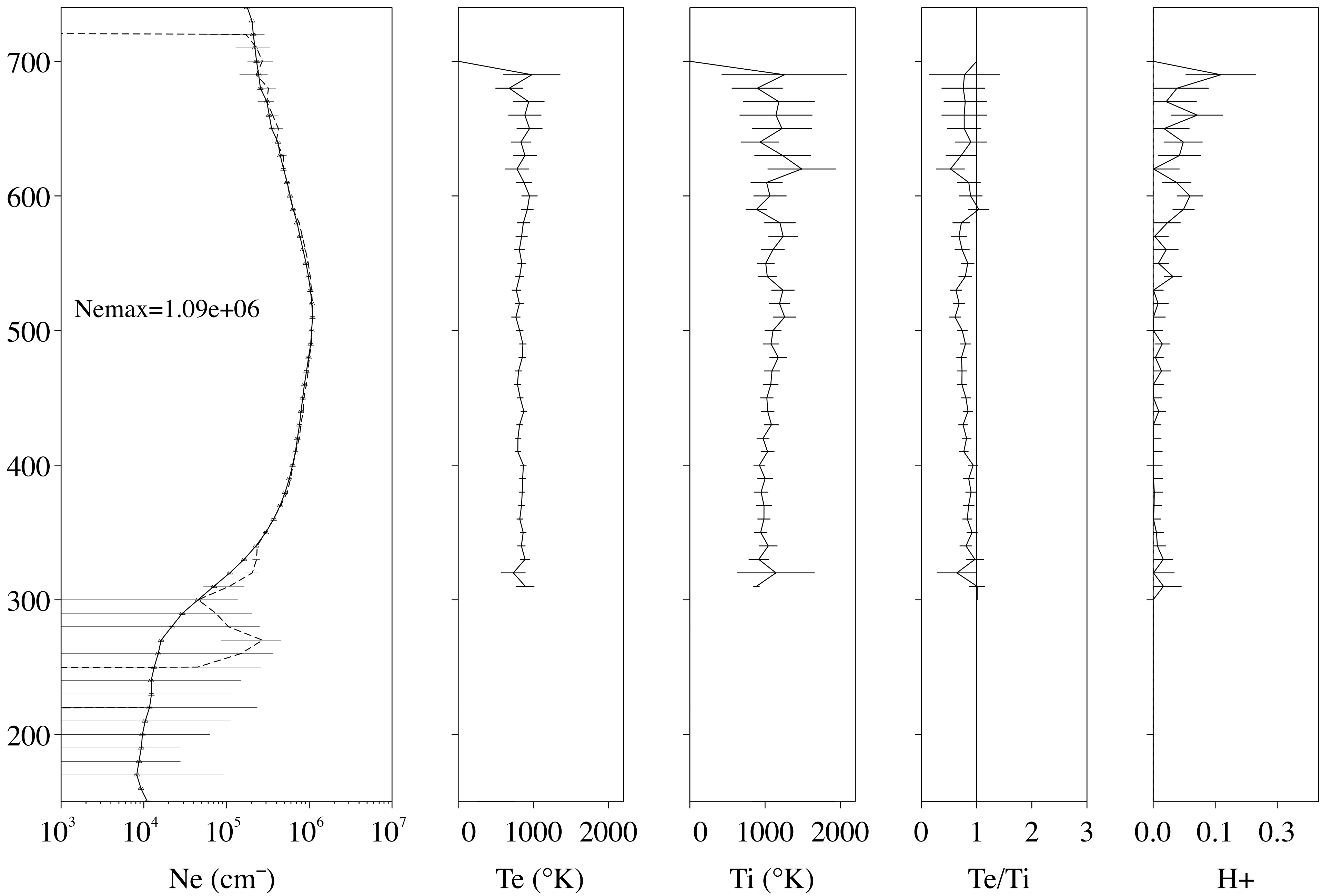
Te < Ti also during the day

March 25, 1994 - Fits including Coulomb Collisions

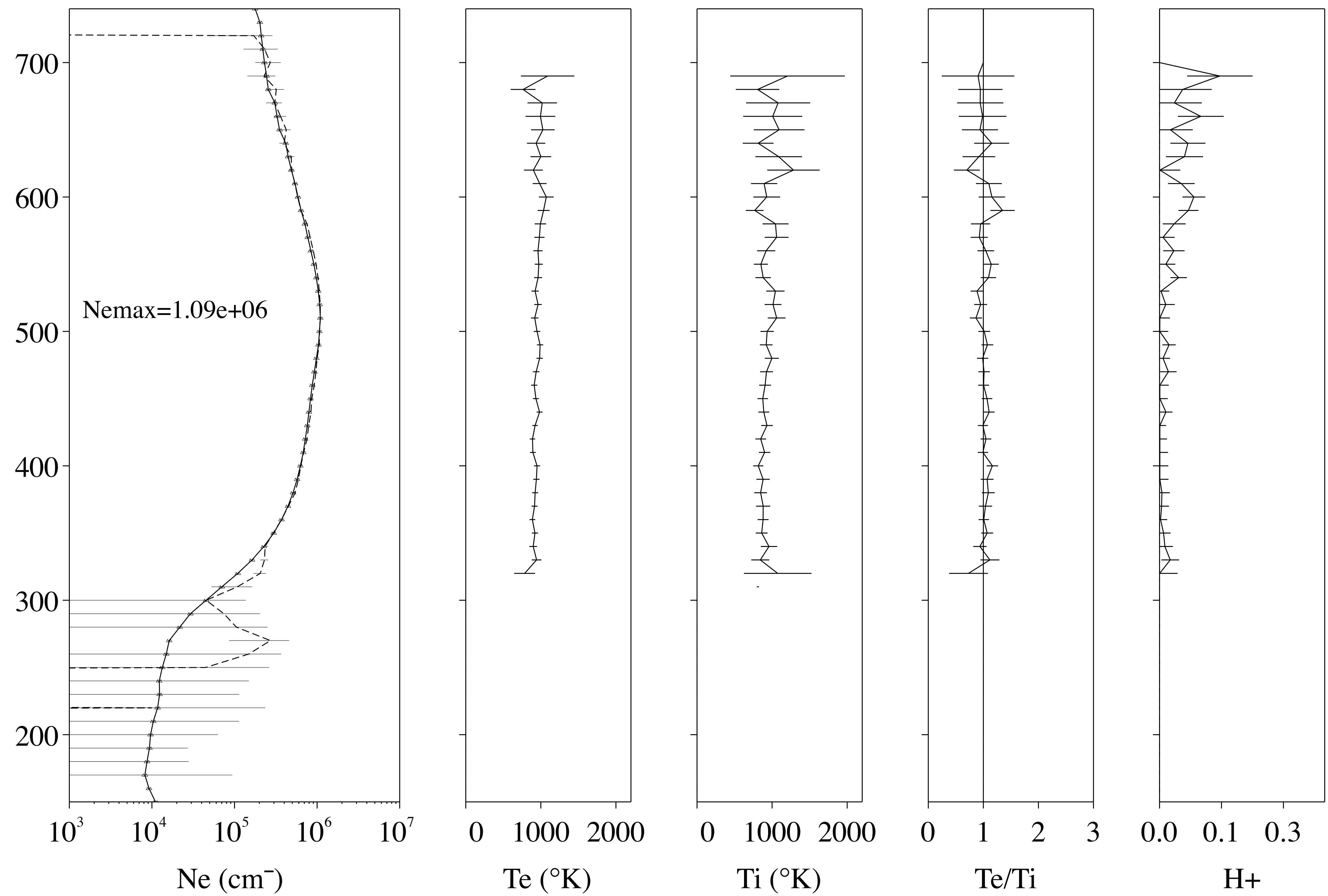
on-axis



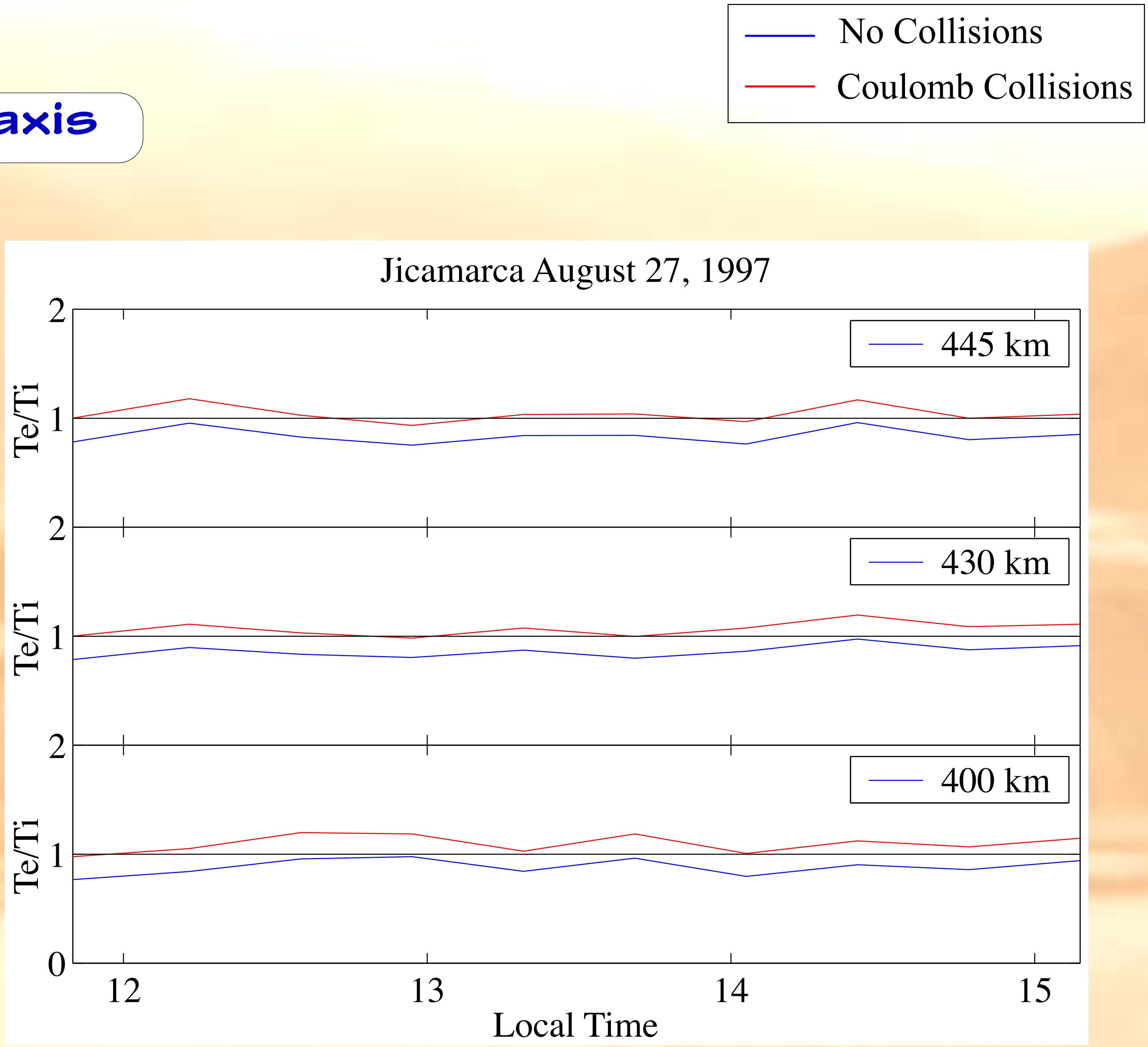
1994/3/25 19:4: 41.6 To 1994/3/25 19:24: 2.8 Nrec= 5120 Nint= 5120 Nmedian = 0 Tx = 15 Crosscorrelation



1994/3/25 19:4: 41.6 To 1994/3/25 19:24: 2.8 Nrec= 5120 Nint= 5120 Nmedian = 0 Tx = 15 Crosscorrelation



on-axis

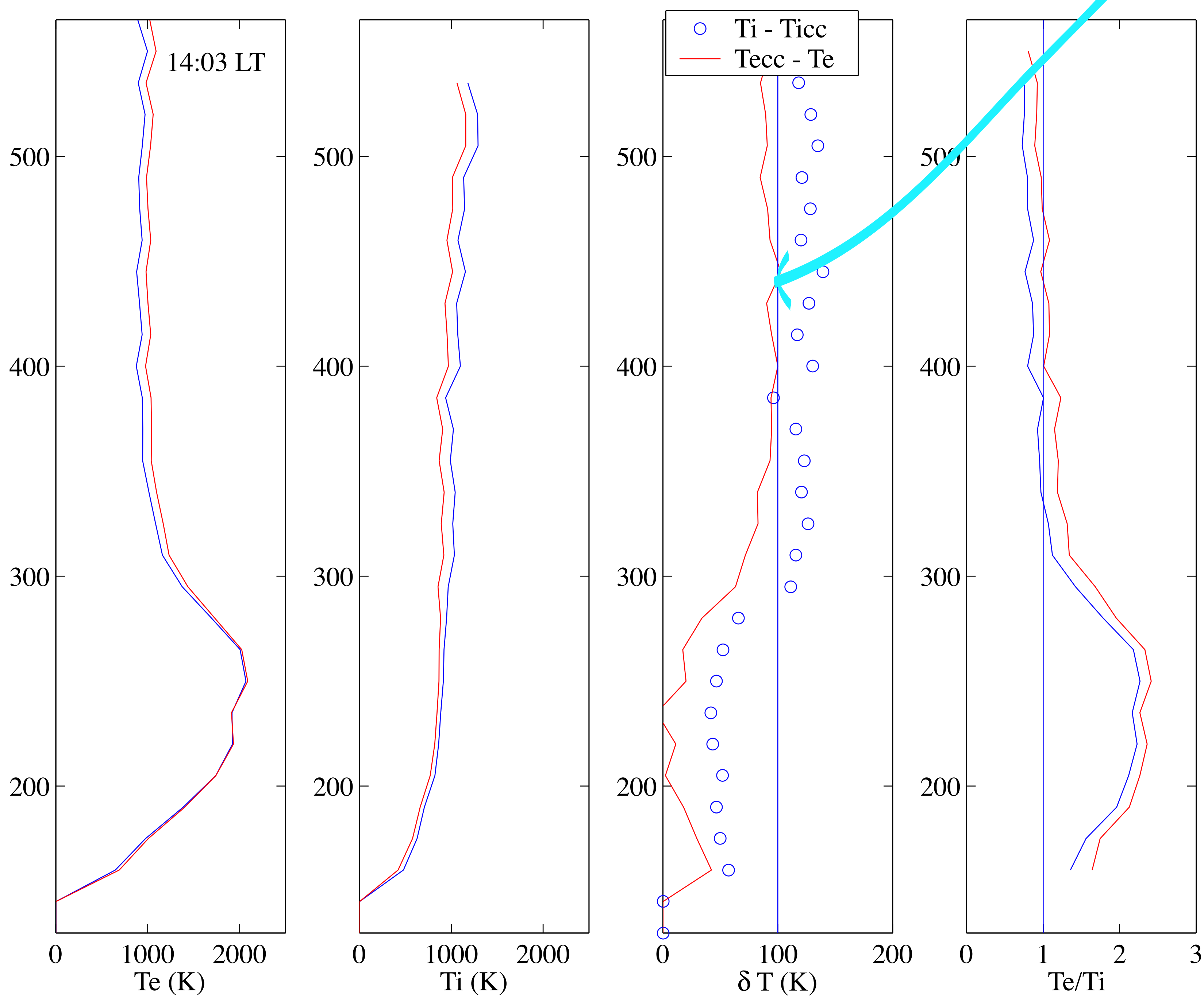


No Collisions
Coulomb Collisions
Jicamarca August 27, 1997
445 km
430 km
400 km
Te/Ti
Te/Ti
Te/Ti
2
1
2
1
2
1
0
12
13
14
15
Local Time

on-axis

Jicamarca August 27, 1997

Both Te and Ti change



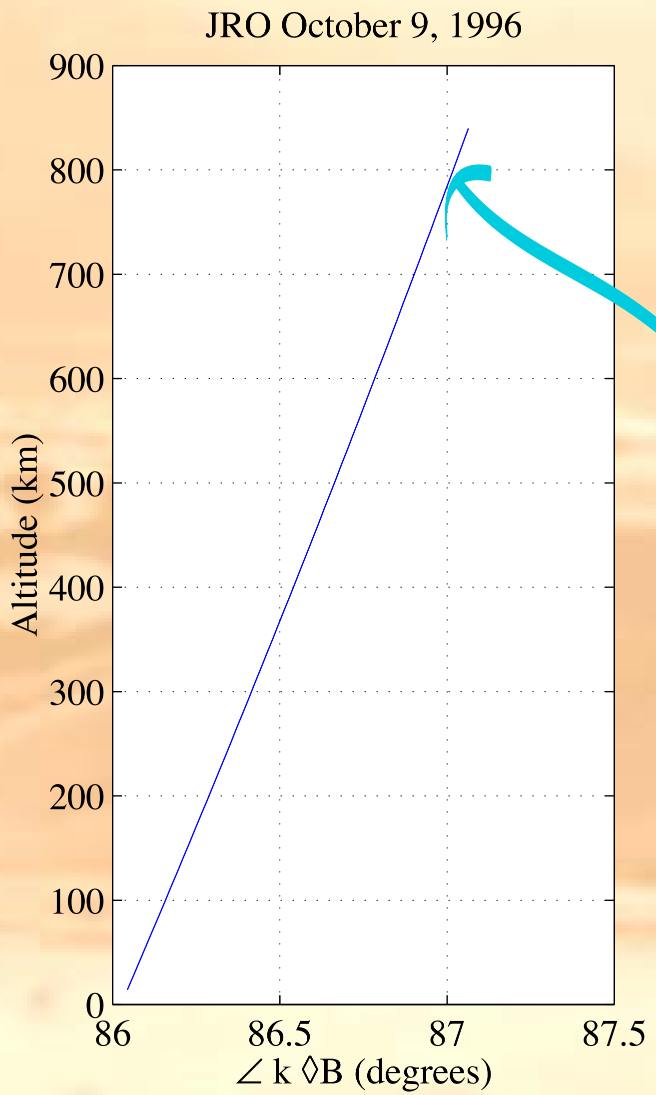
Te 100 K hotter !

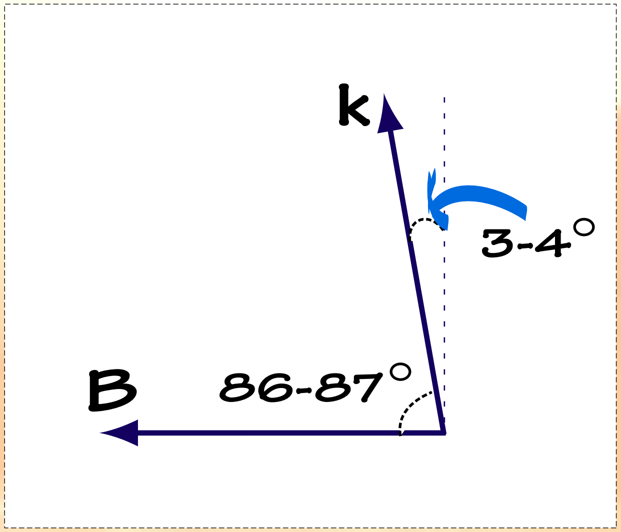
Ti 125+ cooler !

CC

No CC

"4 degrees"

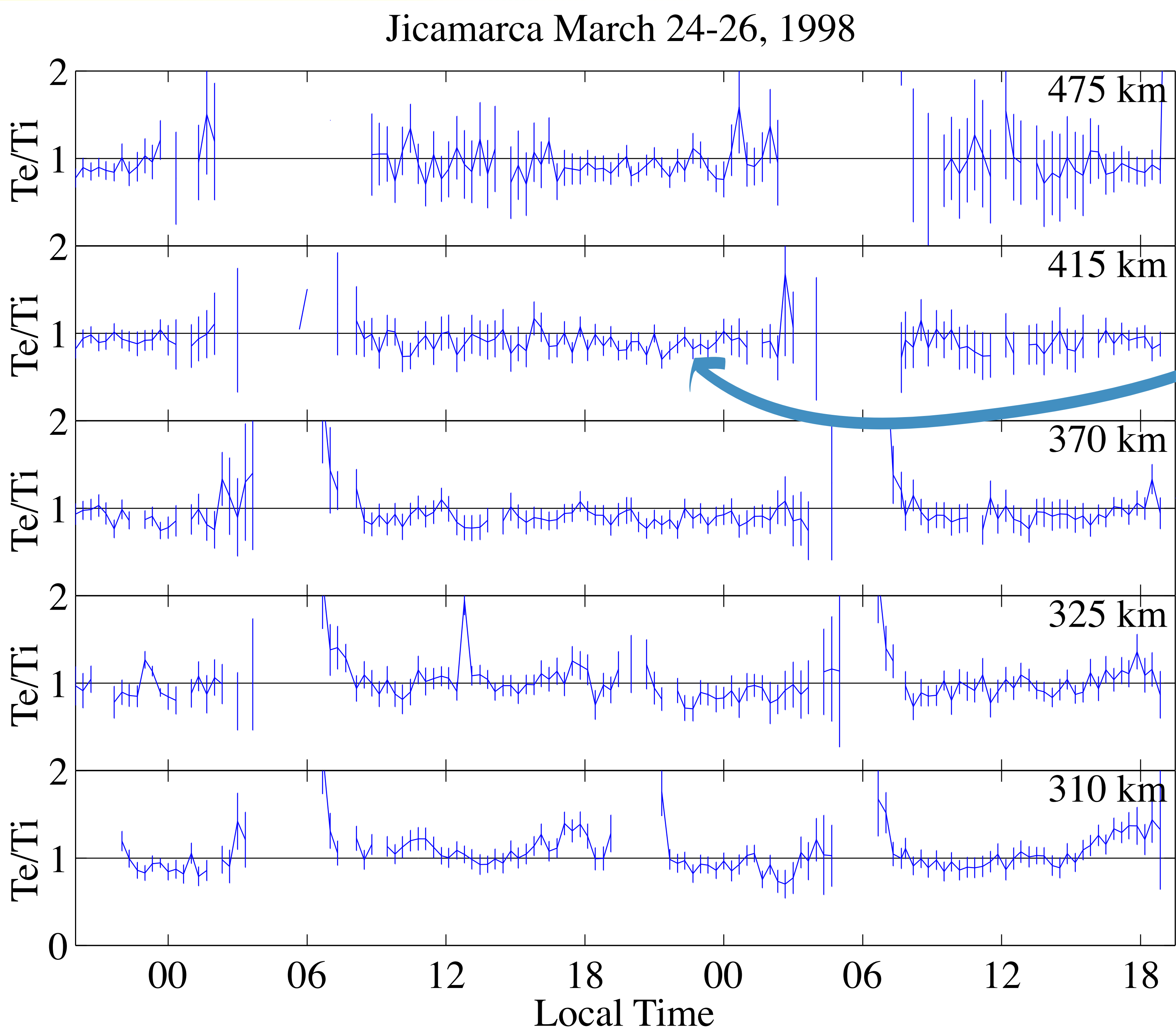




Actually about 3 degrees from perpendicular to B at 800 km

3.5 degrees near 350 km

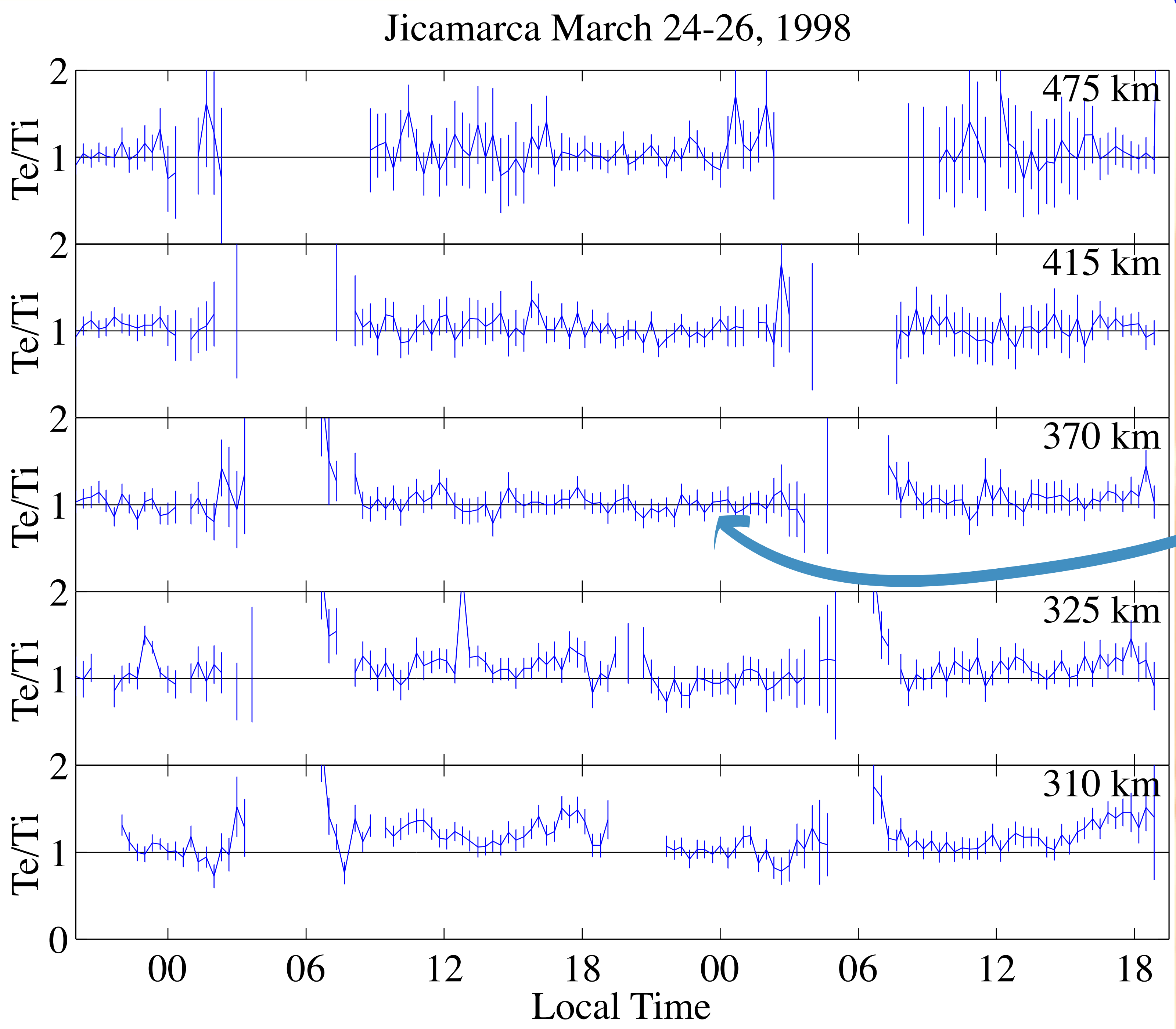
4 deg.



Smaller effect than on-axis, but still a problem

Effect is quite evident at nighttime, but also present during daytime

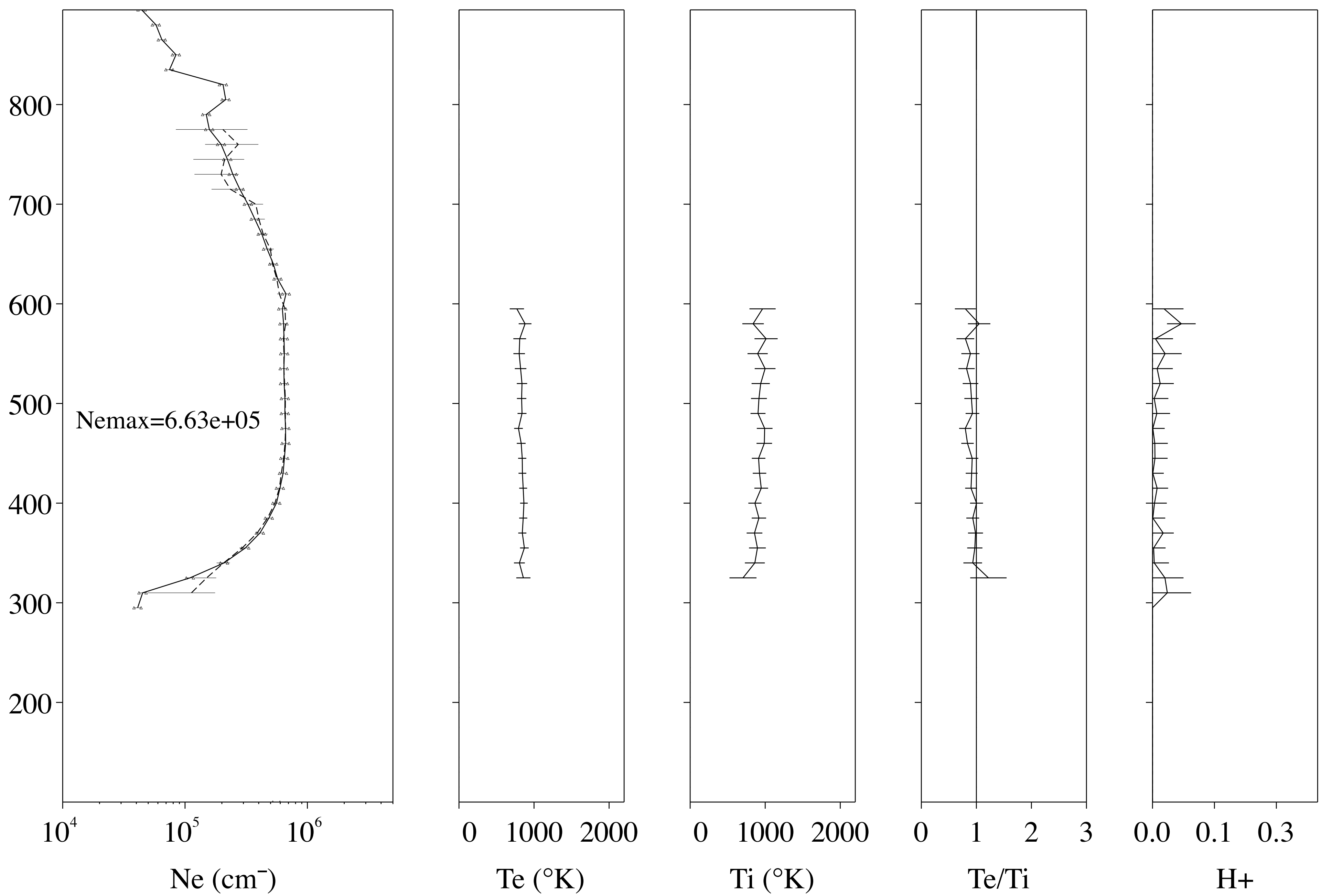
4 deg.



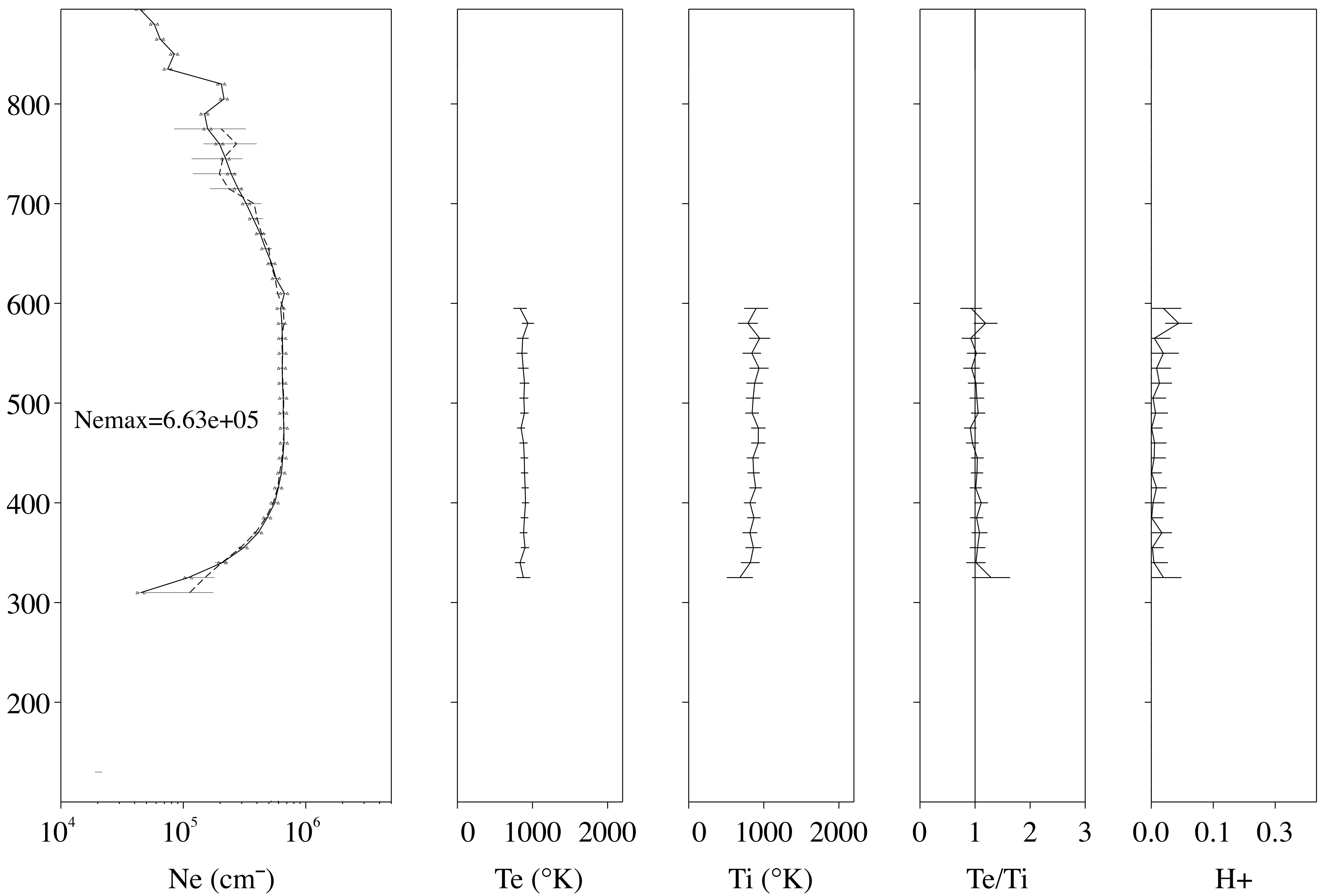
ISR theory with Coulomb collisions correctly interprets the data from this position

Te=Ti at night

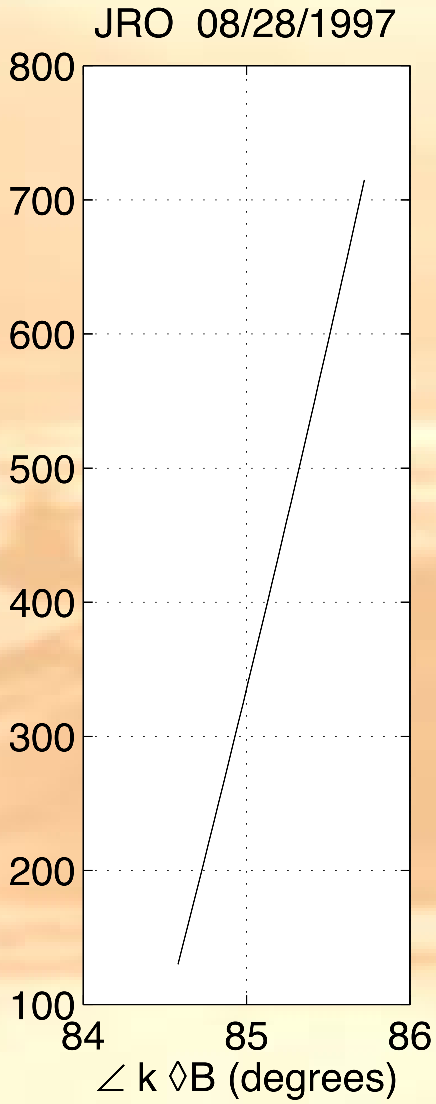
1998/3/25 20:0: 27.0 To 1998/3/25 20:19: 60.0 Nrec= 2686 Nint= 2686 Nmedian = 0 Tx =   15 Crosscorrelation

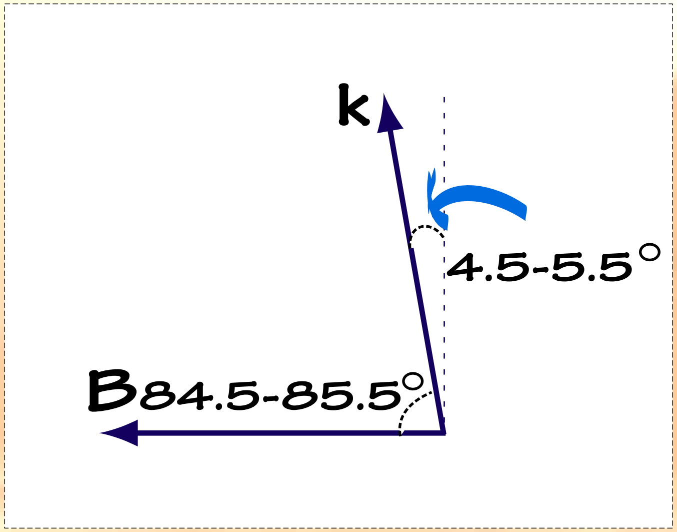


1998/3/25 20:0: 27.0 To 1998/3/25 20:19: 60.0 Nrec= 2686 Nint= 2686 Nmedian = 0 Tx = 15 Crosscorrelation



"6 degrees"

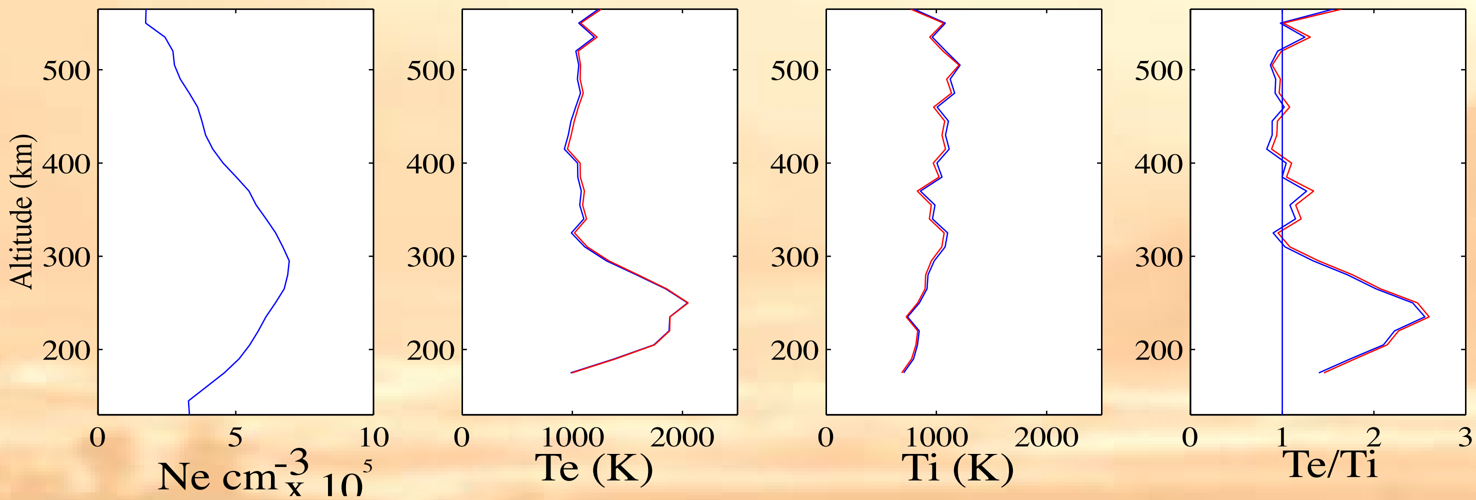




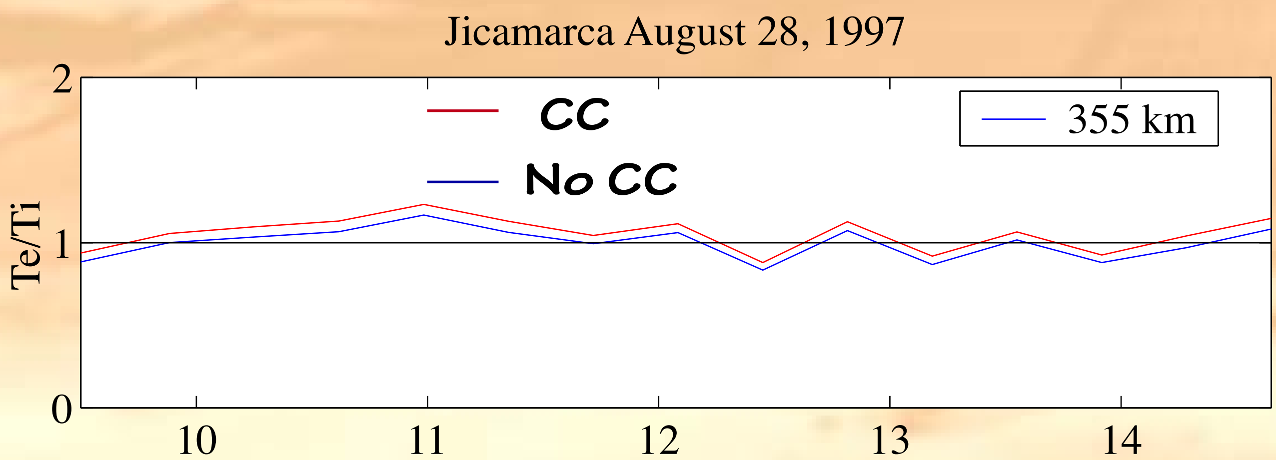
About 5 degrees from perpendicular to B at 350 km

6 deg.

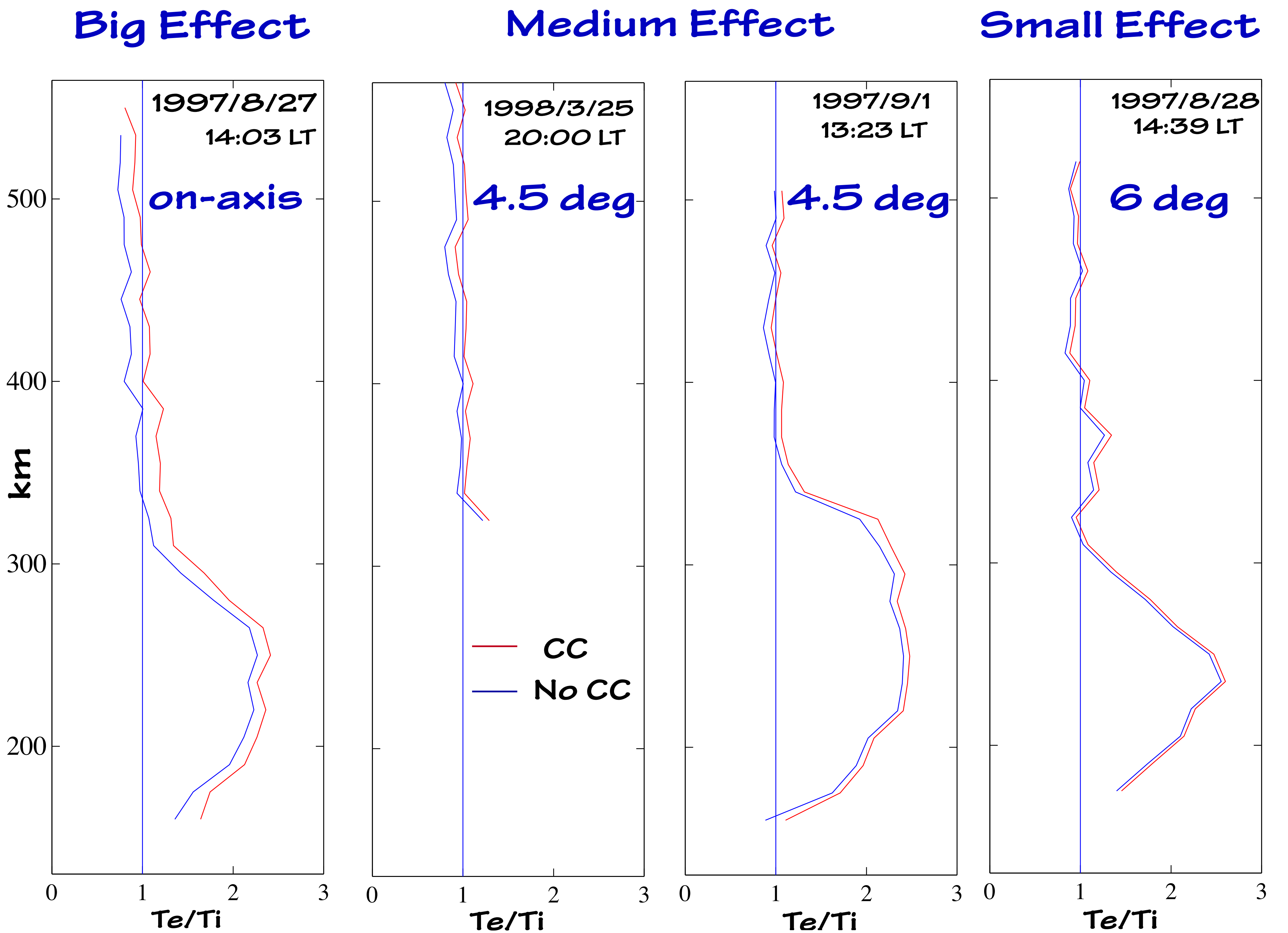
Jicamarca August 28, 1997

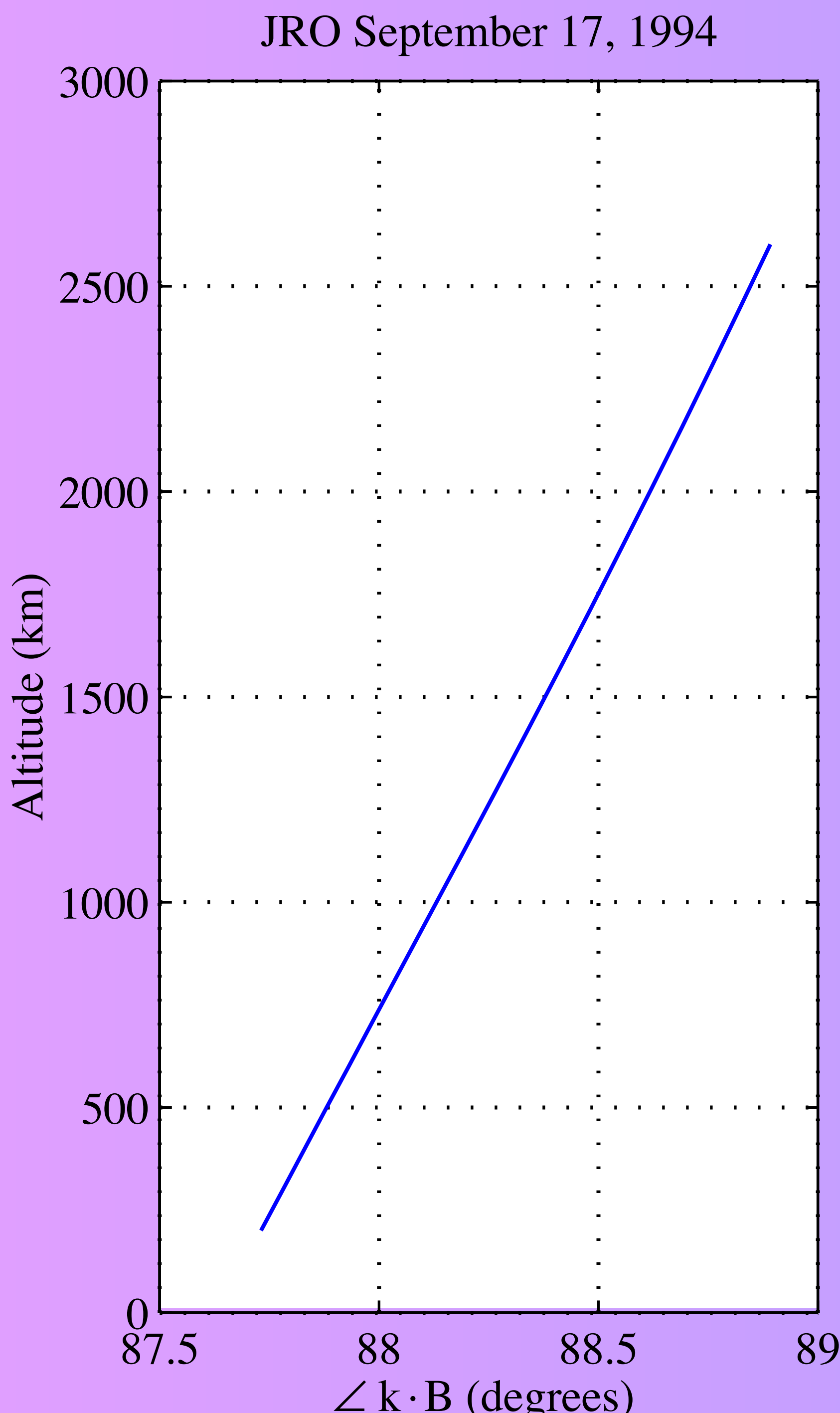


6 deg. position has more clutter problems



Not much difference after accounting for Coulomb collisions effects


Big Effect
Medium Effect
Small Effect
1997/8/27
14:03 LT
on-axis
1998/3/25
20:00 LT
4.5 deg
1997/9/1
13:23 LT
4.5 deg
1997/8/28
14:39 LT
6 deg
CC
No CC
km
500
400
300
200
0
1
2
3
Te/Ti

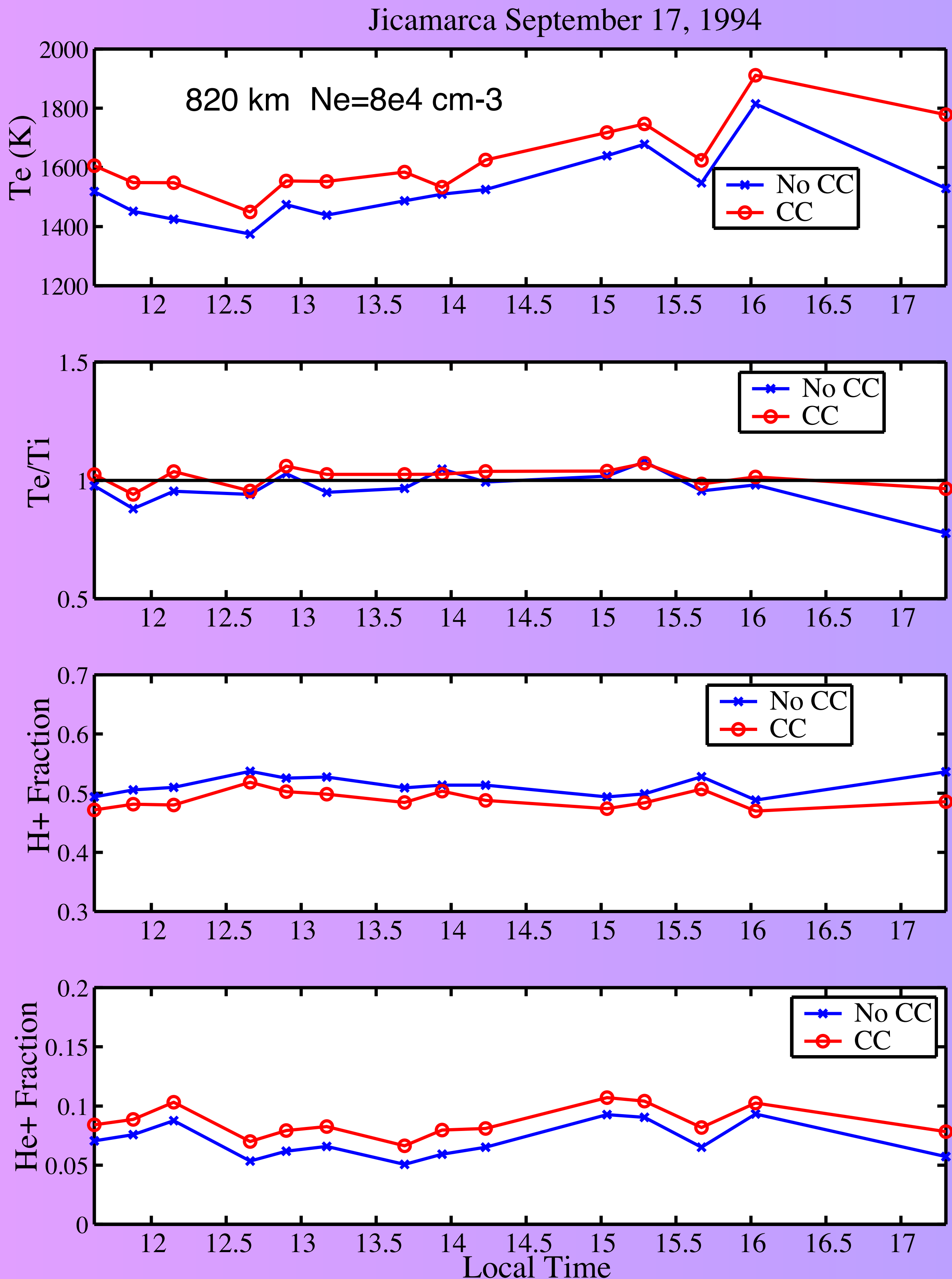


Are topside measurements in the on-axis position affected by Coulomb collisions?

The magnetic field moves; even eight years ago the angle was 2 degrees or less in the topside.

The effect does not fall off all that quickly with decreasing density.

We need to check and see if it is significant.

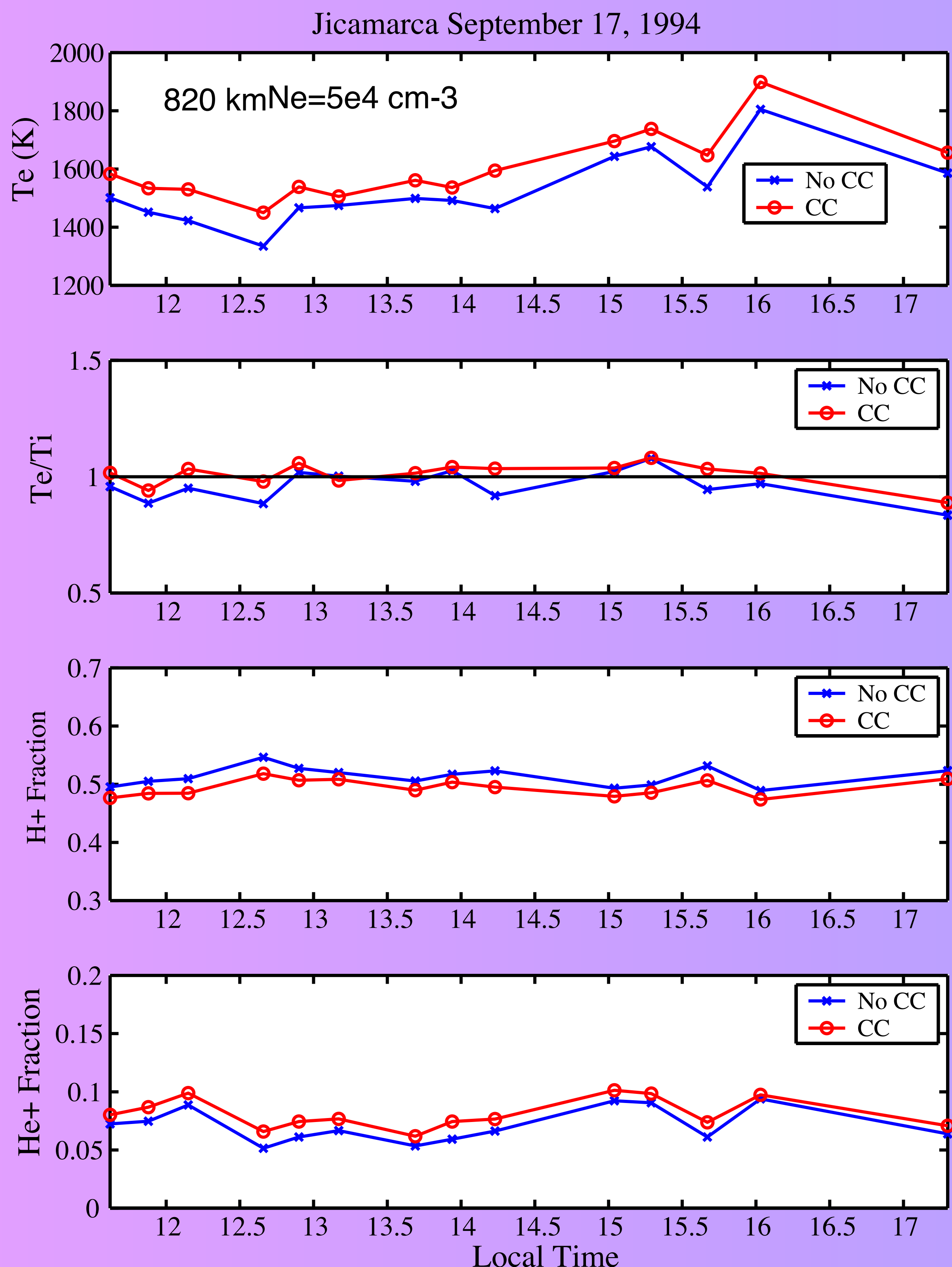


Lower Topside fits with/without Coulomb Collisions.

Constant Density, 80,000

820 km is very near the O^+ H^+ transition height.

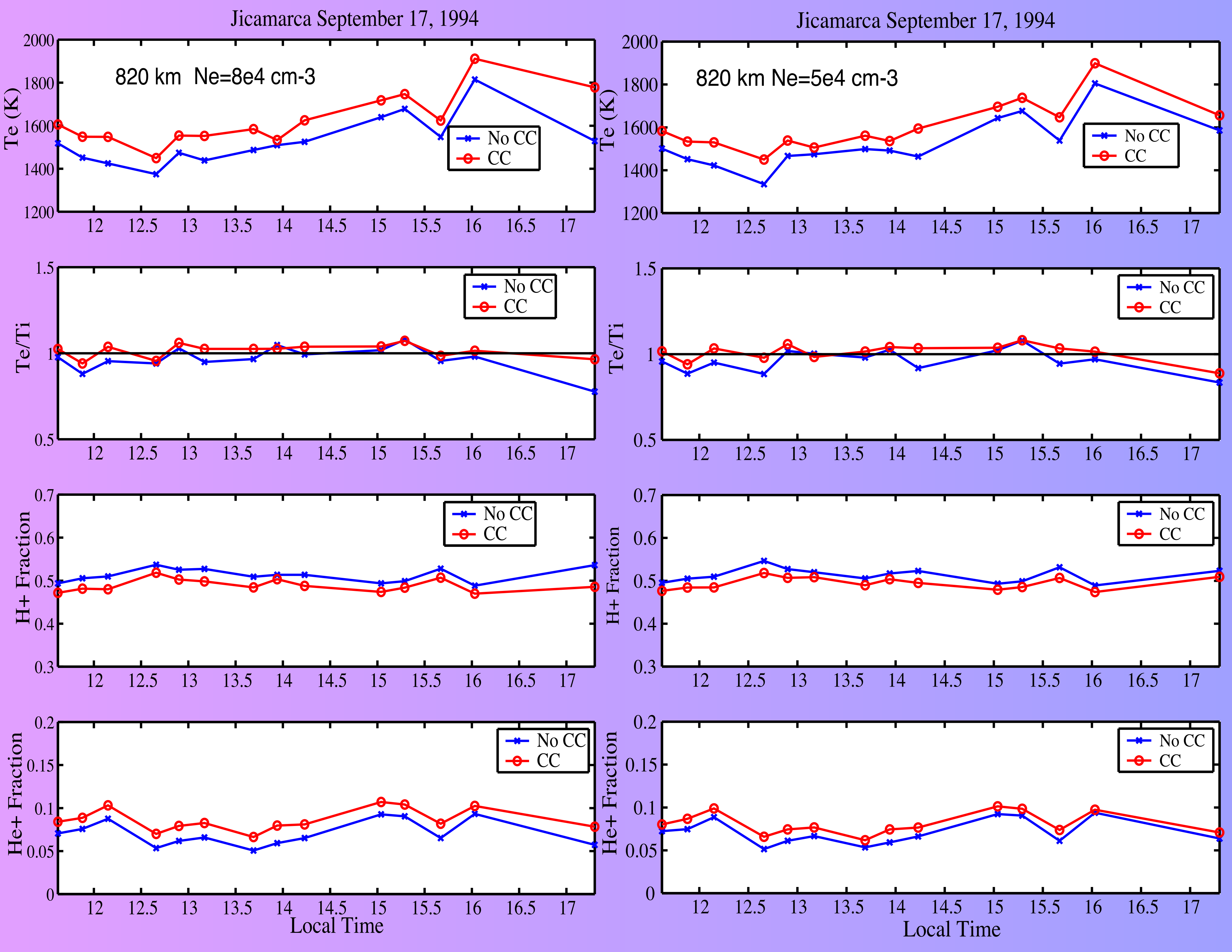
Data supplied by Phil Erickson



Lower Topside fits with/without Coulomb Collisions.

Constant Density, 50,000

Data supplied by Phil Erickson



Jicamarca September 17, 1994
820 km Ne=8e4 cm-3
Te (K)
No CC
CC
Te/Ti
H+ Fraction
He+ Fraction
Local Time
Jicamarca September 17, 1994
820 km Ne=5e4 cm-3
Te (K)
Te/Ti
H+ Fraction
He+ Fraction
Local Time

Summary

The accurate calculations of Sulzer and Gonzalez [1999] solved the problem with the Jicamarca F region temperatures.

The effect of electron Coulomb collisions appears to be significant at topside altitudes near the transition height.