

## Abstract

Unresolved fine structure in the solar transition region (TR) has long been inferred from measurements of density-sensitive line pairs showing low filling factor ( $<0.01$ ). Low filling factor models for the structure of He II source region, however, have not been well studied. We propose a highly structured model of the lower atmosphere in which He II is formed at low filling factors, leading to high emission measure and an optically thin He II line. This transparent TR material is juxtaposed with absorbing chromospheric structures, leading to the nearly uniform center to limb behavior of the He II line as observed.

## Motivation

- Studies of the solar He II 304 Å line have shown a large discrepancy between the observed quiet sun intensity and the intensity predicted by plane-parallel, non-LTE models<sup>[4]</sup> with the models failing to account for the observed intensity by a factor of  $3 \cdot 10^{[1][5]}$ .

- Observation of TR lines other than helium result in small filling factors ( $10^{-2}$ - $10^{-5}$ )<sup>[3]</sup>. Because of this, we expect a priori that a similar-sized filling factor should apply to He II.

- Further, the TR has fine structure at our current observational resolution ( $0.6''$ ) that is not accounted for in uniform plane-parallel models.

- Accounting for the He II brightness:

Intensity  $I \propto \int n^2 f e^{-\tau} dz \rightarrow n_0^2 f l e^{-n_0 f l}$   $f$  is the filling factor,  $l$  is the line of sight length, and we assume a constant density  $n = n_0$

Optical depth  $\tau \propto \int n f dz \rightarrow n_0 f l$

Case I: uniform helium distribution, nearly optically thick

$$\frac{\tau_1}{f_1} = 1 \Rightarrow I_1 \propto n_1^2 l e^{-n_1 l}$$

Increased helium density but less absorption

$$\frac{\tau_2}{f_2} = 10^{-1} \Rightarrow I_2 \propto n_2^2 l e^{-n_2 \tau_2 l}$$

$$f_2 = 10^{-3} \Rightarrow \frac{\tau_2}{f_2} = 10^{-2} \Rightarrow n_2 \approx 44 \cdot n_1$$

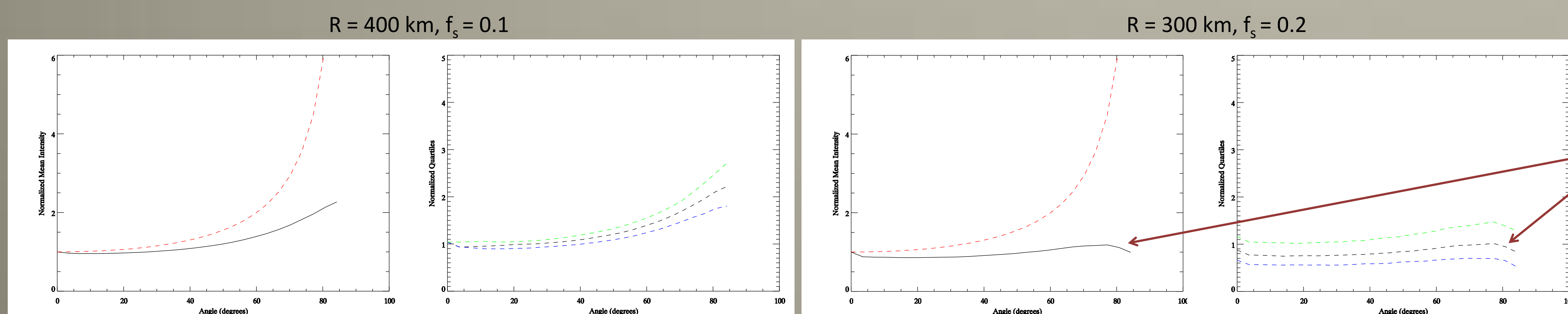
$$f_2 = 10^{-4} \Rightarrow \frac{\tau_2}{f_2} = 10^{-3} \Rightarrow n_2 \approx 133 \cdot n_1$$

Case II: low filling factor, increased intensity

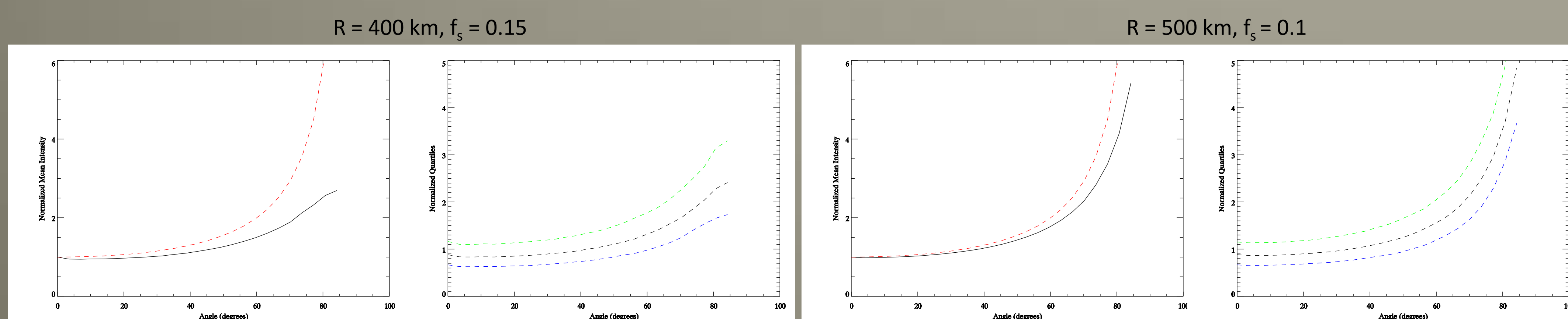
$$f_2 = 10^{-2} \Rightarrow I_2 \propto n_2^2 \cdot 2 \cdot 10^{-3} l e^{-n_2 \tau_2 l}$$

- If we accept higher densities due to low filling factors, we obtain an optically thin line. The problem with a thin line is that it won't reproduce the nearly flat center to limb variation that we observe. The purpose of our model is to consider absorption from the perspective of TR geometry and structure rather than the spectroscopic properties of He II. Similar two-structure models have been proposed for coronal features to explain observed uniform cross sections in bright features and density discrepancies in coronal loops<sup>[2]</sup>.

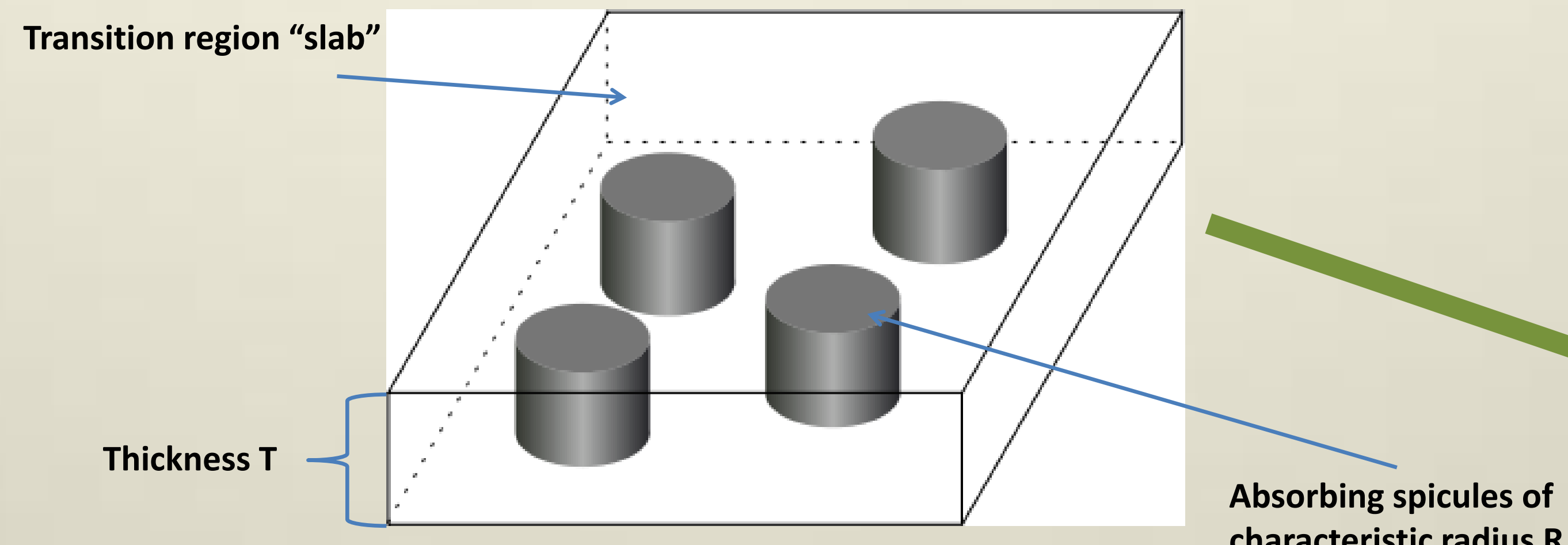
## Model Results



Center to limb variation of the mean intensity (left) and quartiles (right) of the slab. The results have been normalized at  $0^\circ$ . The red dashed line indicates the theoretical result for an optically thin TR. The blue, black, and green dashed lines are the first, median, and third quartiles, respectively.



## Model



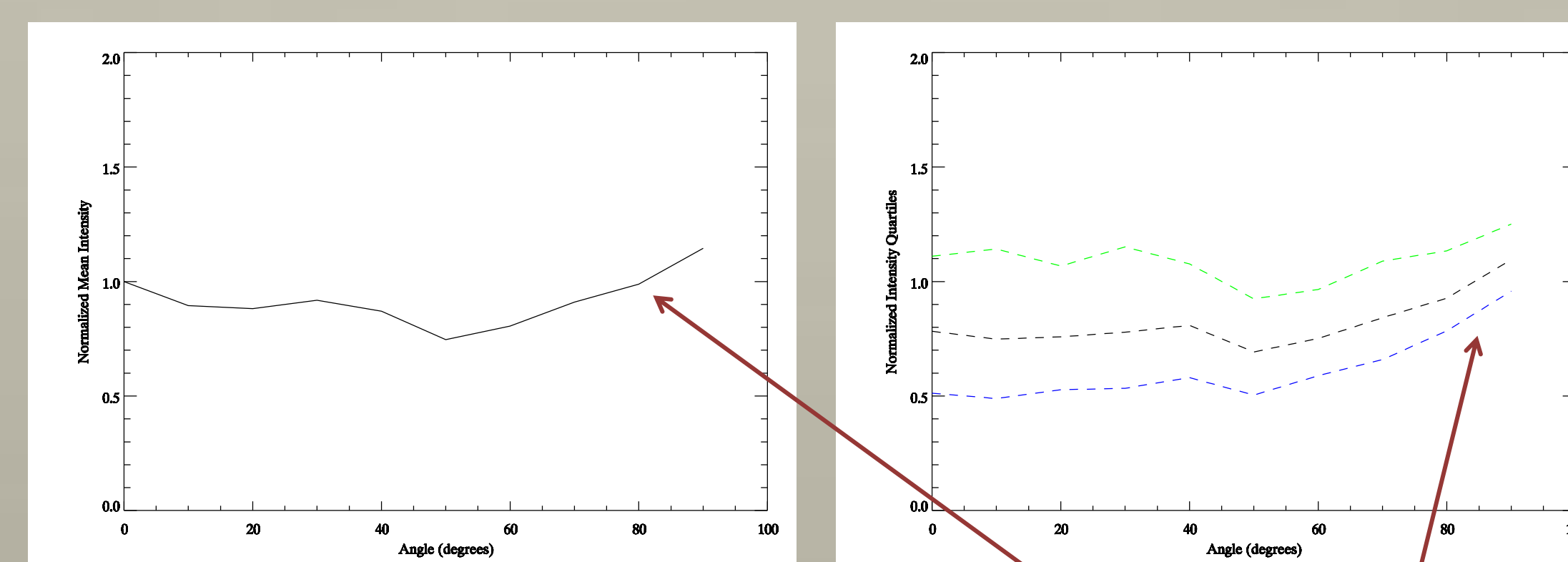
For our model we created a thin slab of emitting material representing the TR. In the slab we placed randomly distributed cylindrical spicules to act as our absorbers, constrained by a parameter we call the spicule fraction ( $f_s$ )—the ratio of spicule-occupied volume to slab volume. If we assume that He II is formed at low filling factor we can neglect absorption by helium in the emitting region of the slab.

The intensity of this slab is obtained by integrating along the line of sight, which begins normal to the surface. The spicules are totally opaque. To simulate a center to limb profile we rotated the slab through  $90^\circ$  relative to the original line of sight.

The slab was constructed such that the model pixel size was  $\approx 400$  km, matching the resolution of the Multi-Order Solar EUV Spectrograph (MOSES) data ( $1.2''$  per two pixels). We performed simulations with  $R = 300$  km –  $800$  km and  $f_s = 0.05$  –  $0.2$ . One limitation of the choice of pixel size was a practical constraint on the thickness  $T$ , which was set for  $T = 2$  Mm.

## Observations

Below are the mean intensity and quartiles for the center to limb variation from MOSES. We see an approximately 15% increase at the limb that corresponds well with the 10-20% brightening from the  $R = 300$  km,  $f_s = 0.2$  model. Qualitatively, we see a generally flat curve that is matched best by smaller width spicules filling about 20% of the slab.



Flat center to limb profile from model matches observations, for small  $R$  or large  $f_s$ .

## Conclusions

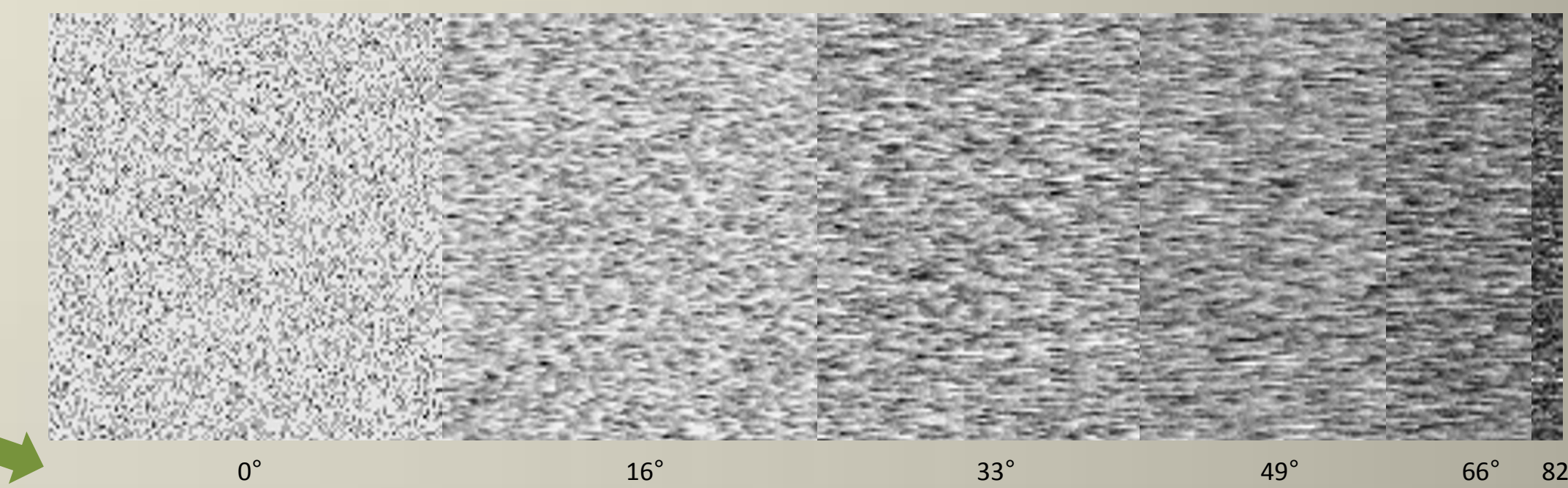
We propose a model of the solar transition region with He II formation at low filling factor ( $<0.01$ ), high density (10-100 times greater), and low optical depth.

- Formation at low filling factor and high densities resolves the discrepancy with observed He II brightness.

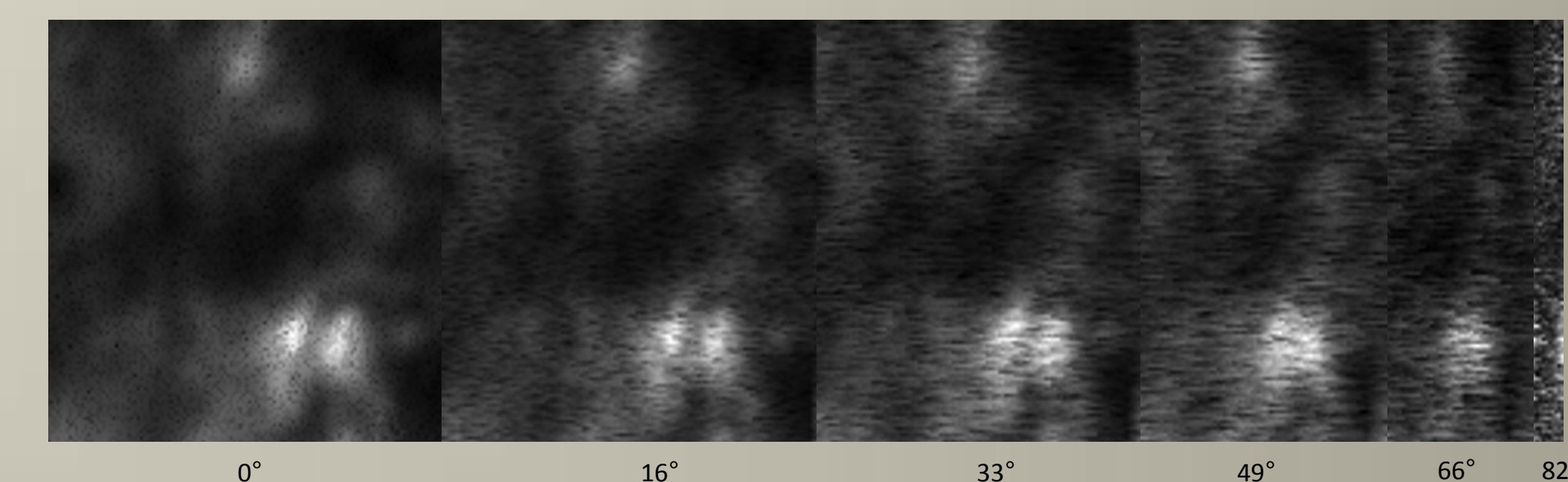
- Opaque chromospheric structures interspersed with this dense, transparent emitting material reproduces the observed center to limb variation of the He II line.

## References

- [1] Andretta, V., et al. 2000, ApJ, 535, 438
- [2] DeForest, C.E. 2007, ApJ, 661, 532
- [3] Dere, K.P., et al. 1987, SoPh, 114, 223D
- [4] Fontenla, J.M., et al. 1990, ApJ, 355, 700
- [5] Macpherson, K.P., & Jordan, C. 1999, MNRAS, 308, 510

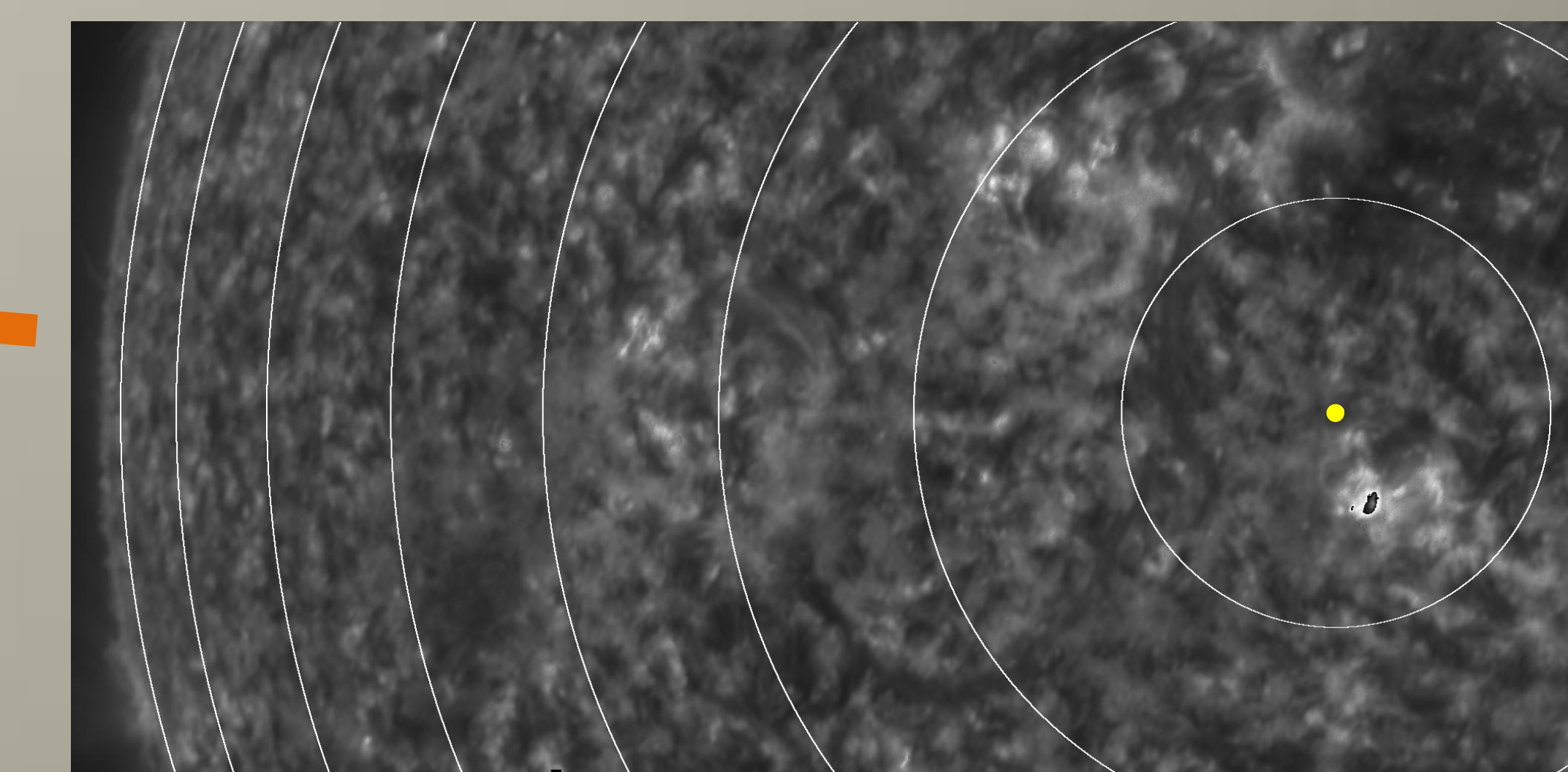


Intensity images for rotations of  $0^\circ$ ,  $16^\circ$ ,  $33^\circ$ ,  $49^\circ$ ,  $66^\circ$ ,  $82^\circ$  from normal incidence. The figure above assumed a uniform intensity, while the one below uses the normal incidence region from the center of the MOSES image. This gives a distribution of intensity at normal incidence for our simulation.



As a comparison for the center to limb profile, we use the results of the MOSES sounding rocket mission, which imaged at  $304 \text{ \AA}$  on 02/08/06 18:45:54 UTC.

The image below is a  $1024 \times 2048$ , 24 s exposure with corrections for oversaturation. The yellow dot marks sun center, while the rings denote regions of  $10^\circ$  rotation from normal incidence at sun center.



## Acknowledgments

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