Modeling the radial distance of the X-ray emitting plasma on the star θ^1 Ori C

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Summary

We recalculate the Mg XI, Si XIII, and S XV forbidden-to-intercombination ratios, using the latest atomic model (ATBASE, v4.3beta2), in conjunction with PrismSPECT.
Comparisons with the old analytic model of Blumenthal, Drake, and Tucker (1972) are also made.
One significant difference is the inclusion of both of the 2 $^3P_{1,2} - 1\ ^1S_0$ transitions.
We also explore the effects of lowering in the star's effective temperature.

The inclusion of the $^3P_2 - {}^1S_0$ transition does not make a significant difference for lower Z elements, but for higher Z elements, it can.

Note also that there is some dependence of the 'low density limit' (R_o) on the plasma temperature. Our simulations use a temperature that produces an ionization fraction of the He-like state that is in excess of 50% (55% for Mg, 89% for Si, 89% for S). Blumenthal, Drake, and Tucker do not include this effect in their model.

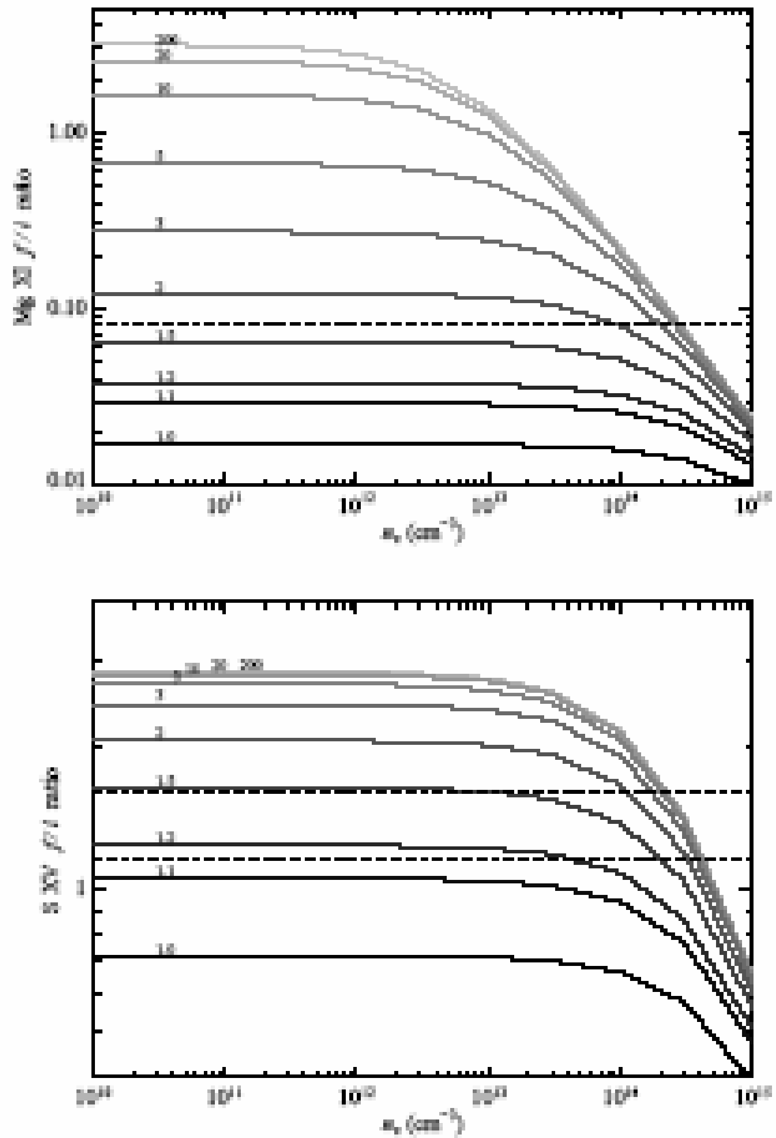


FIG. 13.— He-like f/i ratio versus n_e at various radii from 1–200 R_*, assuming a 45000 K photosphere, for Mg XI (upper panel) and S XV (lower panel). The measured f/i upper and lower bounds from Table 4 are shown as dashed lines. The Mg XI, Si XIII, and S XV suggest a formation radius, $1.2R_* \leq R \leq 1.5R_*$.

This is Figure 13 in the accepted version of the paper. A copy of the paper can be found at: http://astro.swarthmore.edu/~cohen/Papers/gagne_apj_v628_color.pdf

The inferred radial distance of the plasma was:
$r \leq 1.7R_*$ for Mg XI
$1.2R_* \leq r \leq 1.5\ R_*$ for S XV

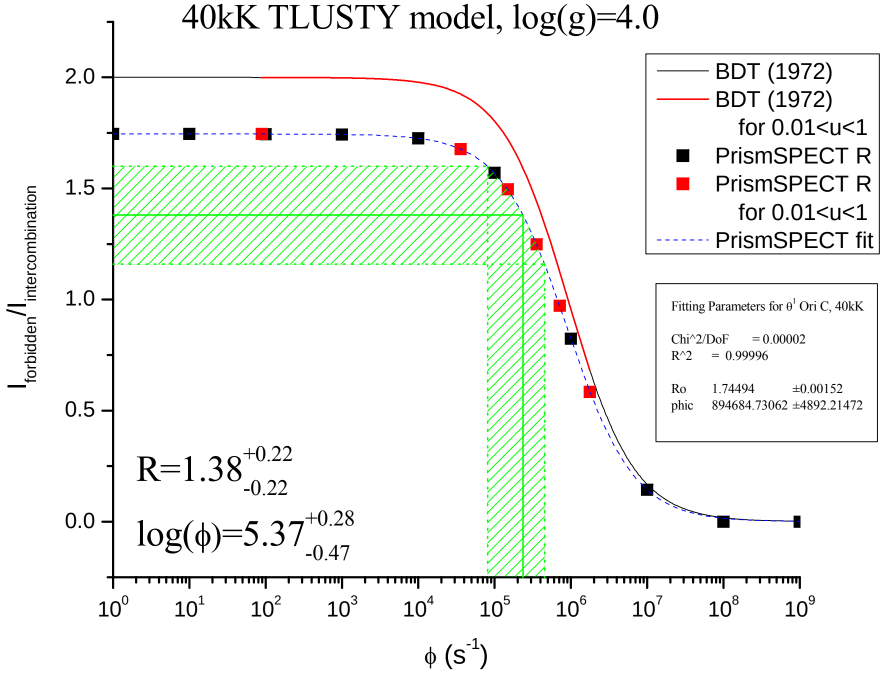
My method for finding the radial distance of the plasma was as follows:

1. I created a plot of $R(f/i)$ vs. φ.
2. I fit a BDT-style function ($R=R_0/(1+\varphi/\varphi_c)$) to several PrismSPECT simulations in order to determine PrismSPECT's values for R_0 and φ_c.
3. This new function enabled me to plot the PrismSPECT f/i ratio against the radial distance (I used $u=R_*/r$ because that is how it appears in the formula for the dilution factor).
4. The radial distance can then be found from the plot or from the function I used to fit the data.

On the following pages, you will find two versions of each plot: one for a 40kK TLUSTY model atmosphere, and one for a 45kK atmosphere.

Sulfur: the Dependence of *f/i* upon photoexcitation rate, φ

R vs. ϕ, S XV, θ^1 Ori C
40kK TLUSTY model, log(g)=4.0



For each of these plots, the solid line corresponds to Blumenthal, Drake, and Tucker's (1972) analytic model. The individual data points (red and black) are the *f/i* ratio calculated by PrismSPECT for a particular value of φ.

The dashed blue line is a BDT-type function that fits the PrismSPECT points and determines the parameters R_0 and φ_c.

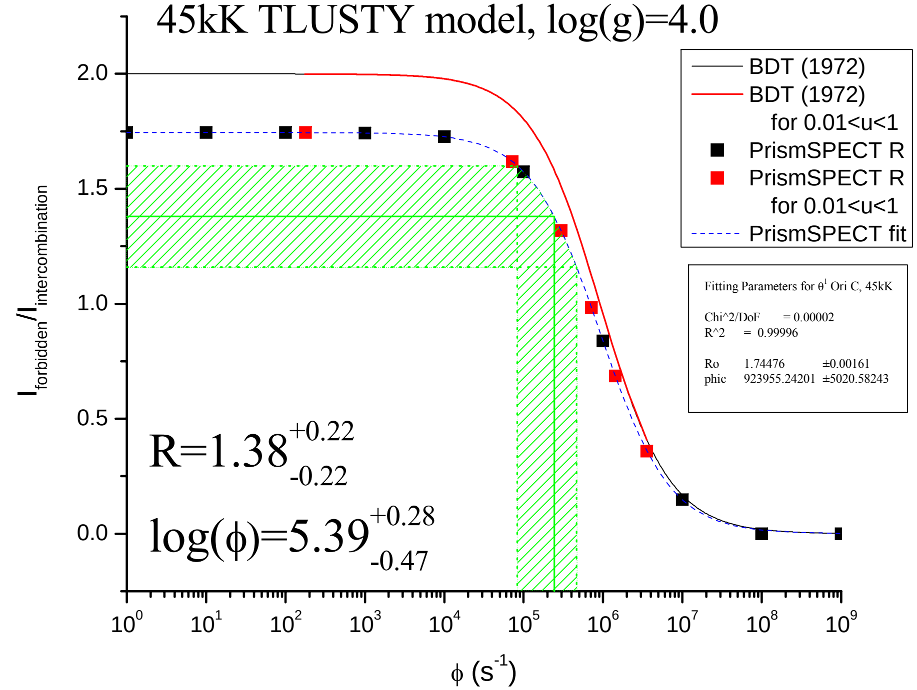
The shaded region is the area of 1σ uncertainty.

The red points and the red line segments are used for the plots on the following pages. They represent f/i values that have been calculated for specific radial distances ($1R_* < r < 100R_*$).

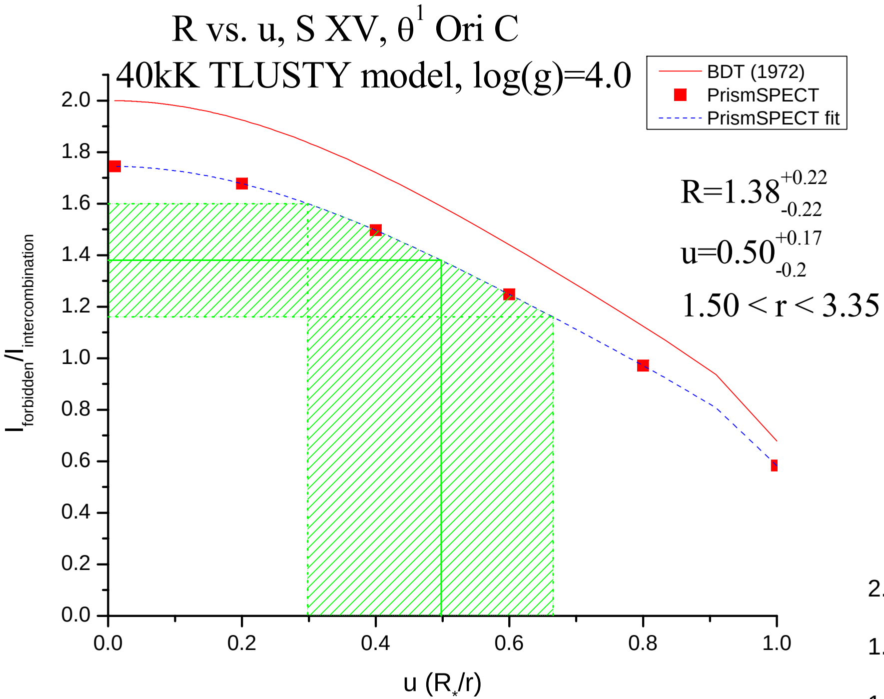
The black points are the *f/i* ratios calculated by PrismSPECT for $\varphi=10^x$.

Executive summary: Don't worry about the difference between the red and black points. The green area represents the 1-sigma uncertainty according to the data and PrismSPECT.

R vs. ϕ, S XV, θ^1 Ori C
45kK TLUSTY model, log(g)=4.0



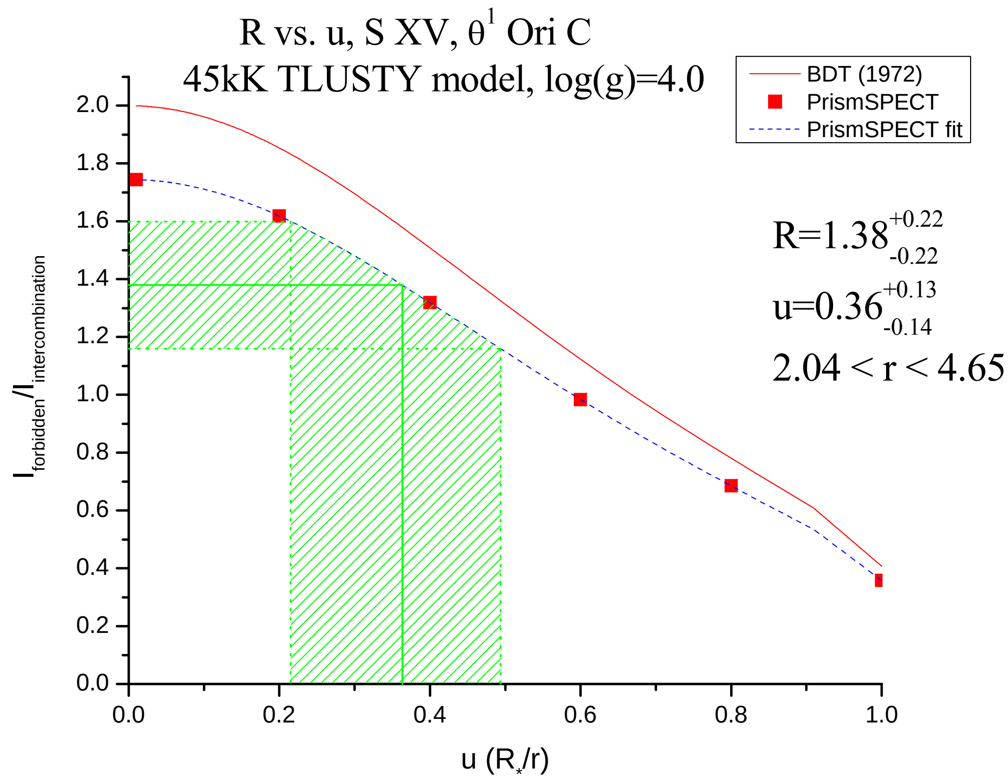
Dependence of *f/i* upon scaled radius, $u=R_*/r$



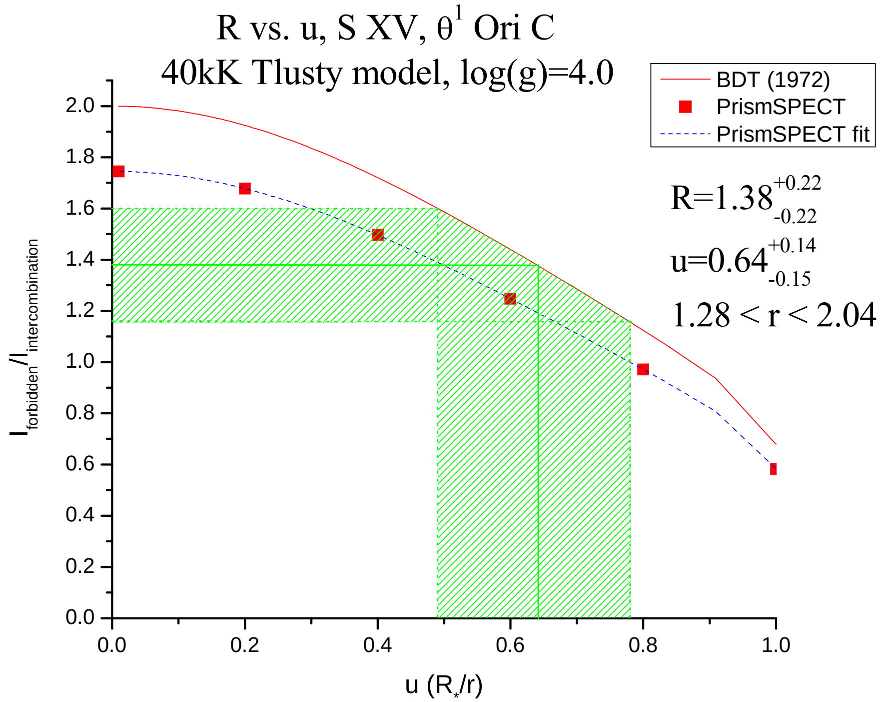
Assuming a cooler effective temperature for the star (which now seems more likely), it can be seen that the radial distance of the X-ray emitting plasma is between $1.5R_*$ and $3.35R_*$.

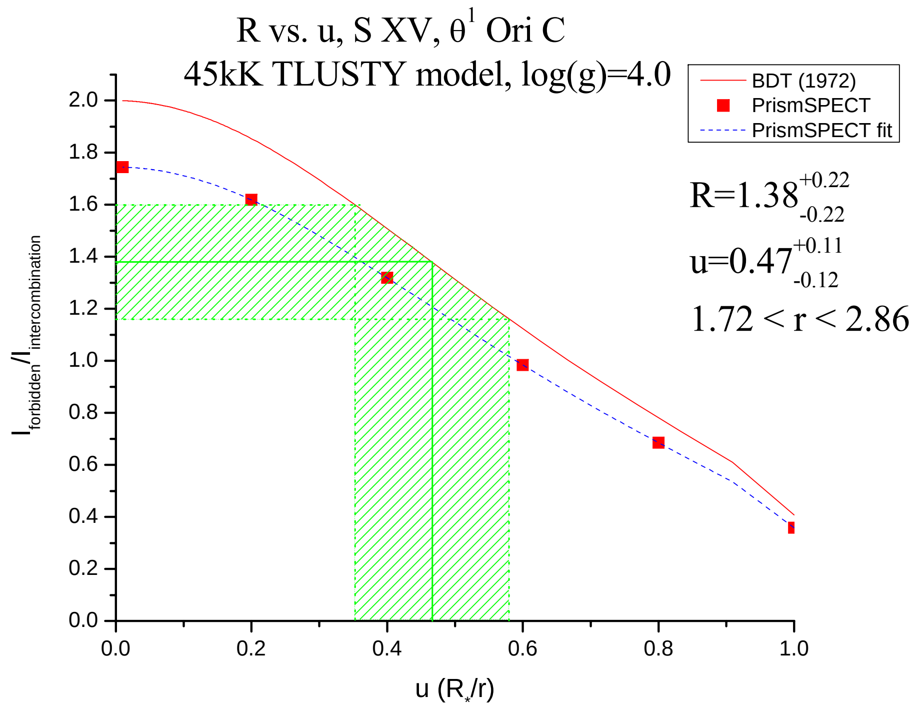
The hotter model – reported on in the paper – gives 2.0 to 4.65 R_* when we use the newer atomic model.

	40kK	40kK	45kK	45kK
r/R_*	T_{rad}(eV)	*f/i*	T_{rad}(eV)	*f/i*
1	3.38	0.58	3.89	0.36
1.25	2.69	0.97	3.09	0.69
1.67	2.26	1.25	2.60	0.98
2.5	1.82	1.50	2.09	1.32
5	1.27	1.68	1.47	1.62
100	0.28	1.75	0.33	1.75

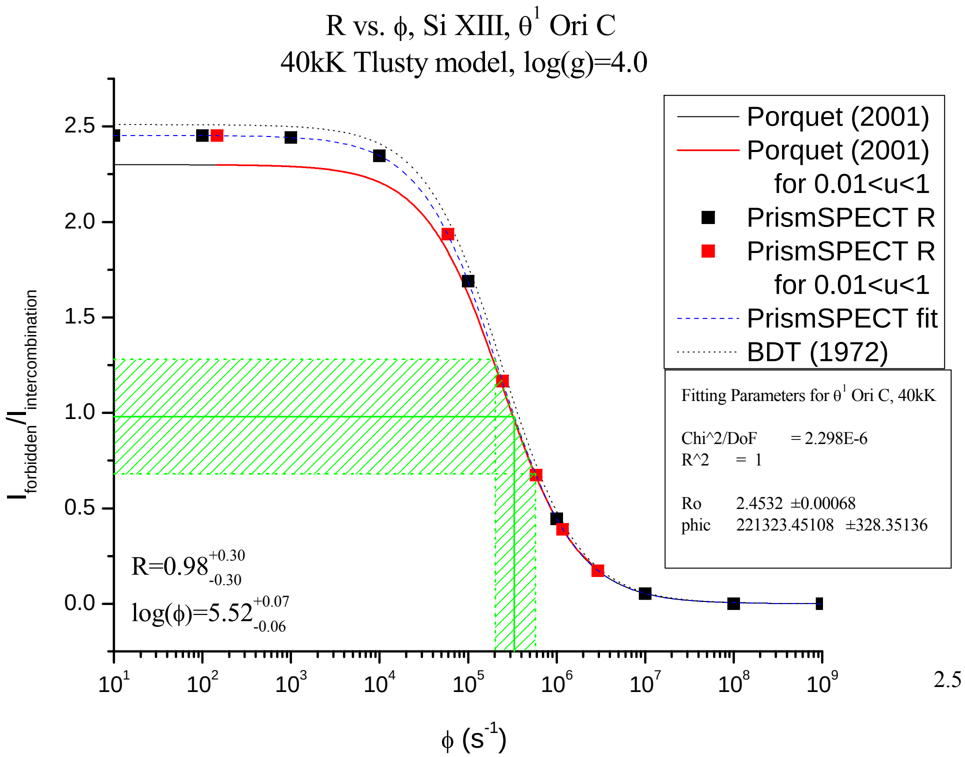


Dependence of *f/i* upon scaled radius, u=R*/r, using the Blumenthal, et al. (1972) model





Silicon: the Dependence of *f/i* upon photoexcitation rate, φ



For each of these plots, the solid line corresponds to Blumenthal, Drake, and Tucker's (1972) analytic model. The individual data points (red and black) are the *f/i* ratio calculated by PrismSPECT for a particular value of φ.

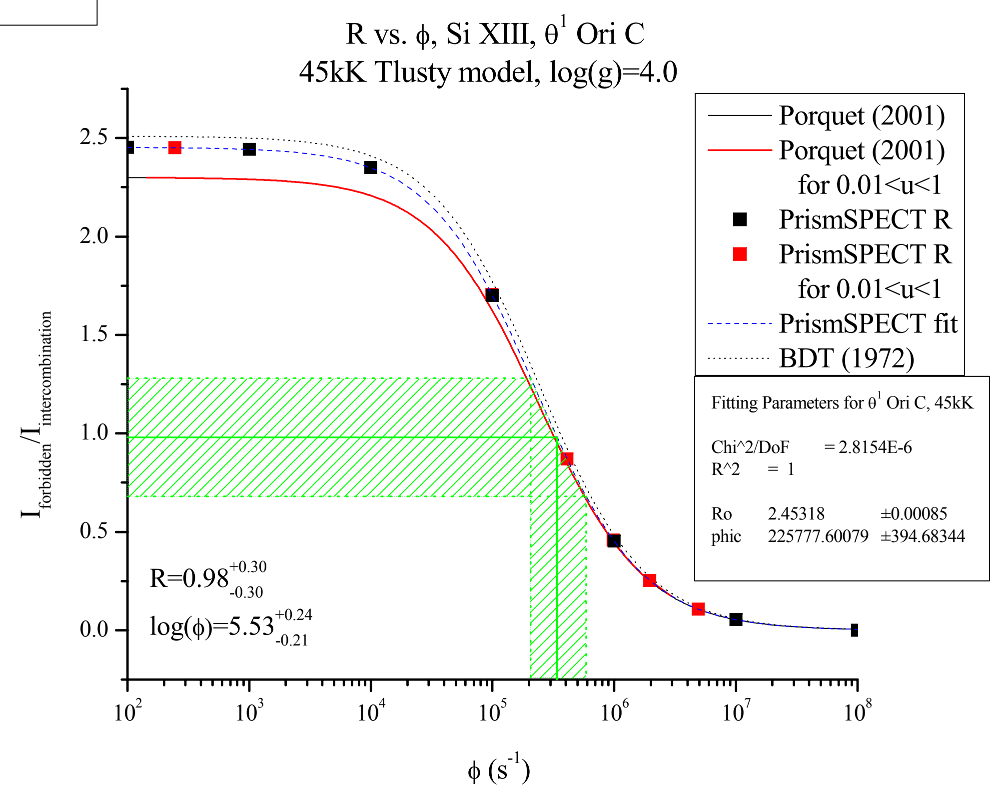
The dashed blue line is a BDT-type function that fits the PrismSPECT points and determines the parameters R_0 and φ_c.

The shaded region is the area of 1σ uncertainty.

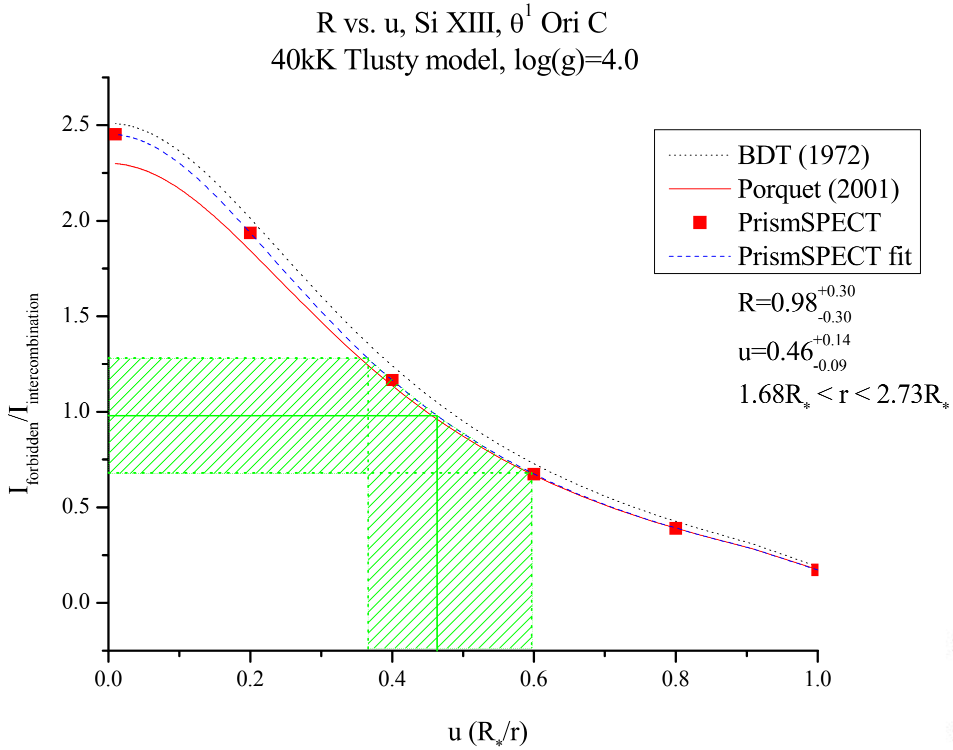
The red points and the red line segments are used for the plots on the following page. They represent f/i values that have been calculated for specific radial distances ($1R_* < r < 100R_*$).

The black points are the f/i ratios calculated by PrismSPECT for $\varphi=10^x$.

Executive summary: Don't worry about the difference between the red and black points. The green area represents the 1-sigma uncertainty according to the data and PrismSPECT.



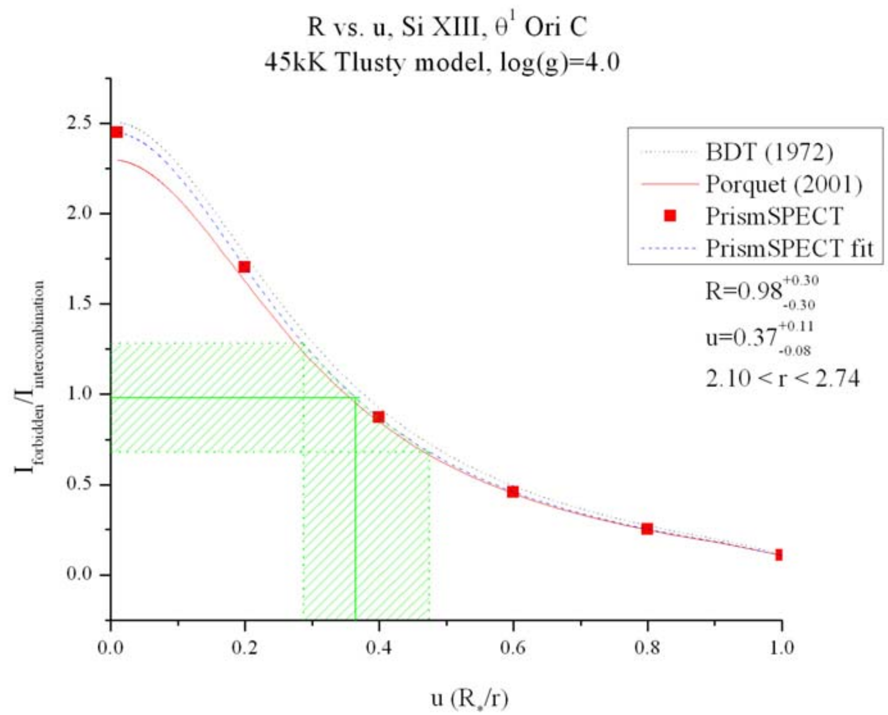
Silicon: Dependence of *f/i* upon scaled radius, $u = R_*/r$



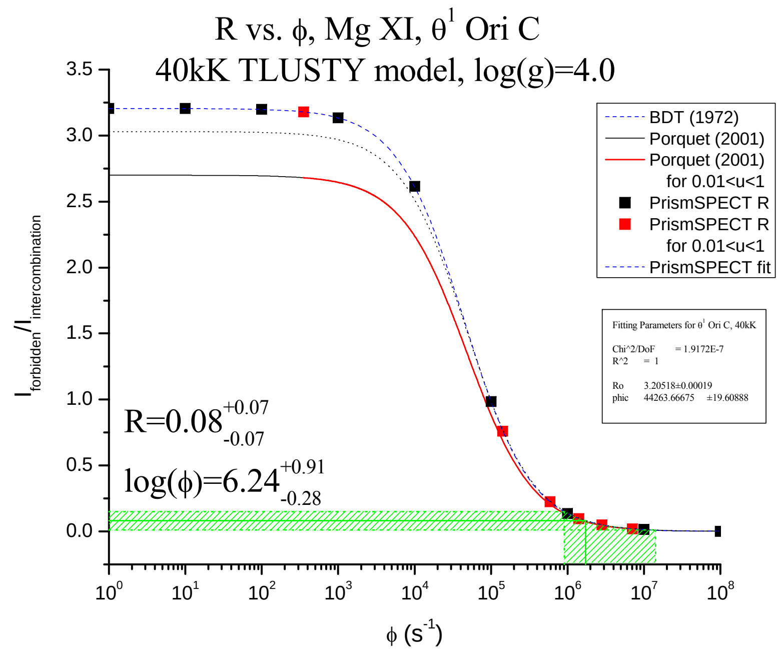
Assuming a cooler effective temperature for the star (which now seems more likely), it can be seen that the radial distance of the X-ray emitting plasma is between 1.68 and 2.73R_*.

Note that the PrismSPECT line differs significantly from the other two lines for the hotter model. BDT would predict 1.6 < *r* < 2.5R_*

	40kK	40kK	45kK	45kK
r/R_*	T_{rad}(eV)	f/i	T_{rad}(eV)	f/i
1	3.29	0.17	3.71	0.11
1.25	2.62	0.39	2.95	0.25
1.67	2.20	0.67	2.48	0.46
2.5	1.77	1.17	1.99	0.87
5	1.24	1.94	1.40	1.70
100	0.28	2.45	0.31	2.45



Magnesium: the Dependence of *f/i* upon photoexcitation rate, φ



The red points and the red line segments are used for the plots on the following page. They represent f/i values that have been calculated for specific radial distances ($1R_* < r < 100R_*$).

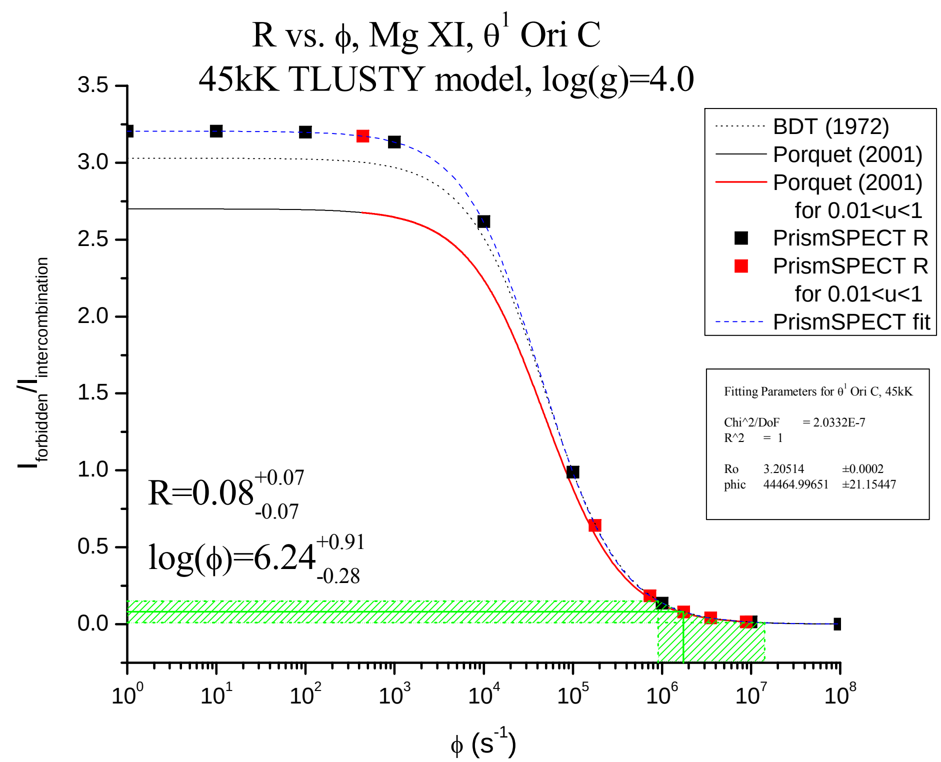
The black points are the f/i ratios calculated by PrismSPECT for $\varphi=10^x$.

Executive summary: Don't worry about the difference between the red and black points. The green area represents the 1-sigma uncertainty according to the data and PrismSPECT.

For each of these plots, the solid line corresponds to Blumenthal, Drake, and Tucker's (1972) analytic model. The individual data points (red and black) are the *f/i* ratio calculated by PrismSPECT for a particular value of φ.

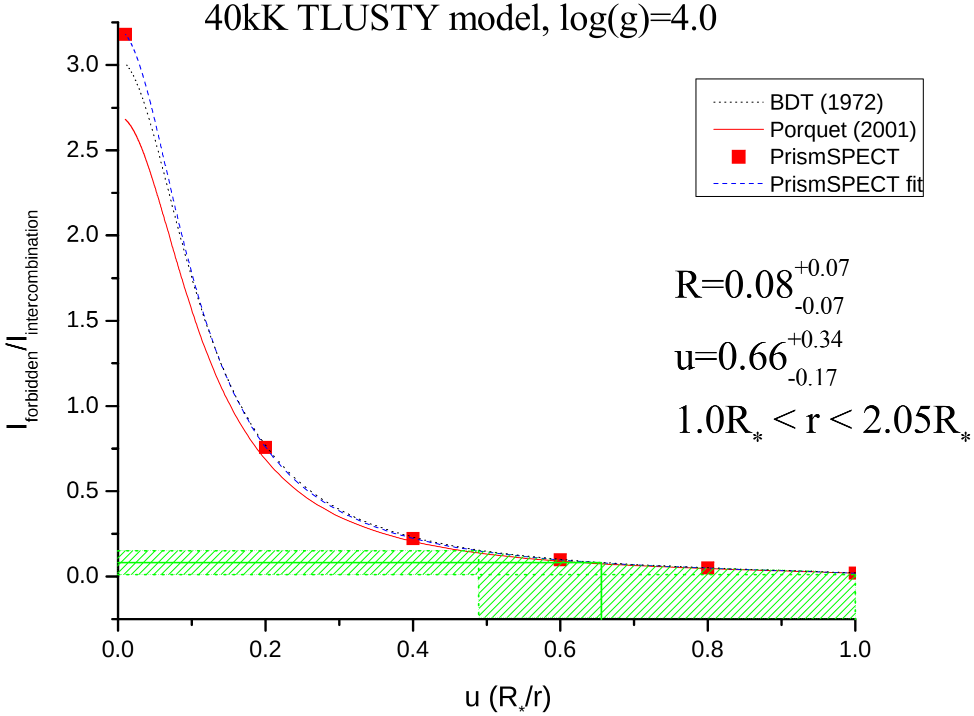
The dashed blue line is a BDT-type function that fits the PrismSPECT points and determines the parameters R0 and φc.

The shaded region is the area of 1σ uncertainty.



Dependence of *f/i* upon scaled radius, u=R*/r

R vs. u, Mg XI, θ^1 Ori C
40kK TLUSTY model, log(g)=4.0

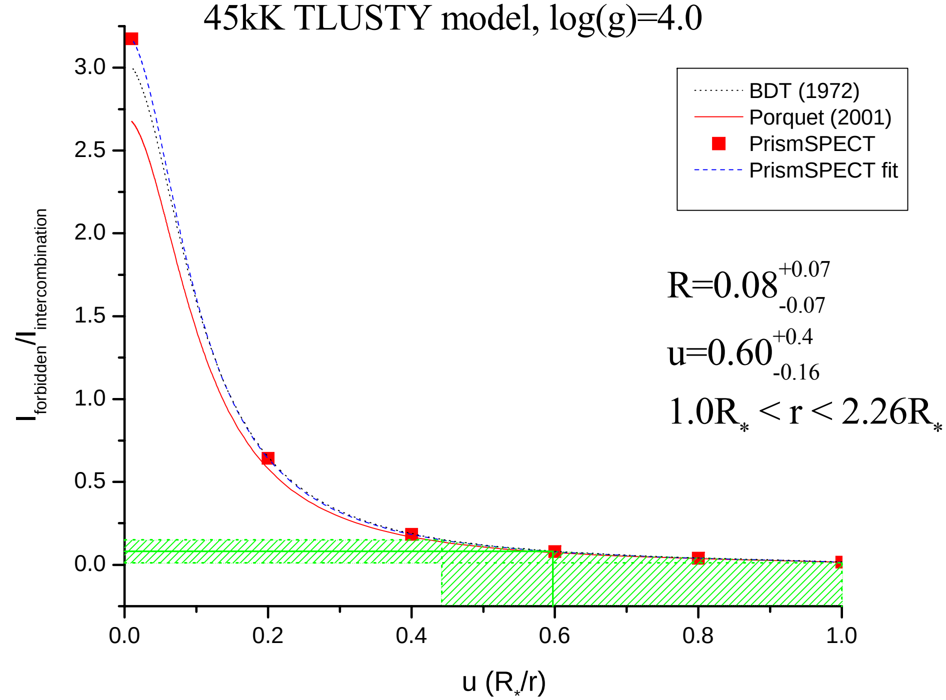


Assuming a cooler effective temperature for the star (which now seems more likely), it can be seen that the radial distance of the X-ray emitting plasma is between 1.0 and 2.05R*. The hotter model gives results with an upper limits only a bit higher.

The Blumenthal et al. model gives very similar results in both cases.

	40kK	40kK	45kK	45kK
r/R_*	T_{rad}(eV)	f/i	T_{rad}(eV)	f/i
1	3.58	0.02	3.82	0.02
1.25	2.85	0.05	3.03	0.04
1.67	2.40	0.10	2.55	0.08
2.5	1.93	0.22	2.05	0.18
5	1.35	0.76	1.44	0.64
100	0.30	3.18	0.32	3.17

R vs. u, Mg XI, θ^1 Ori C
45kK TLUSTY model, log(g)=4.0



Conclusions

For the recalculated PrismSPECT results, the f/i ratios predict the following radial distances for the X-ray emitting plasma:

For a 40kK star:
Mg XI: $1.0\ R_* < r < 2.1\ R_*$
Si XIII: $1.7\ R_* < r < 2.7\ R_*$
S XV: $1.5\ R_* < r < 3.4\ R_*$

For a 45kK star:	compare values quoted in the paper:
Mg XI: $1.0\ R_* < r < 2.3\ R_*$	$1.0 < r < 1.7\ R_*$
S XIII: $2.1\ R_* < r < 2.7\ R_*$	
S XV: $2.0\ R_* < r < 4.7\ R_*$	$1.2 < r < 1.5\ R_*$

For the Blumenthal, Drake, and Tucker (1972) model, the *f/i* ratios predict the following radial distances:

For a 40kK star:
Mg XI: $1.0\ R_* < r < 2.0\ R_*$
S XIII: $1.6\ R_* < r < 2.5\ R_*$
S XV: $1.3\ R_* < r < 2.0\ R_*$

For a 45kK star:
Mg XI: $1.0\ R_* < r < 2.3\ R_*$
S XIII: $2.1\ R_* < r < 2.7\ R_*$
S XV: $1.7\ R_* < r < 2.9\ R_*$

Conclusions, pt. II

Although each ion can exist in different regions and at different temperatures, the data and modeling is consistent with a radius of formation of 1.7 to 2.0 R_* for the cooler model and 2.1 to 2.3 R_* for the hotter model.

This represents both the overlap region of parameter space for the three ions and the overlap between PrismSPECT and Blumenthal et al. modeling.

Note that the Blumenthal et al. result, assuming a cooler atmosphere model, isn't that far off from the result we have in the manuscript now. And the effective temperature may, in fact, be even cooler than this.

So, perhaps the constraints from the S XV *f/i* aren't that different than what we have now. But they could certainly be higher, as with the PrismSPECT calculations. The new results for Mg are a bit higher (larger r/R_*) than what we quote in the paper[1]. The primary atomic rates in PrismSPECT are very similar to the older ones used by Blumenthal et al., but PrismSPECT models the recombination cascades that contribute to the populations of the *n*=2 states in more detail.

[1]In the paper, we use the *f/i* measurement for the upper limit on Mg, while in this presentation, we use the measurement + 1 sigma uncertainties; this accounts for most of the small difference.