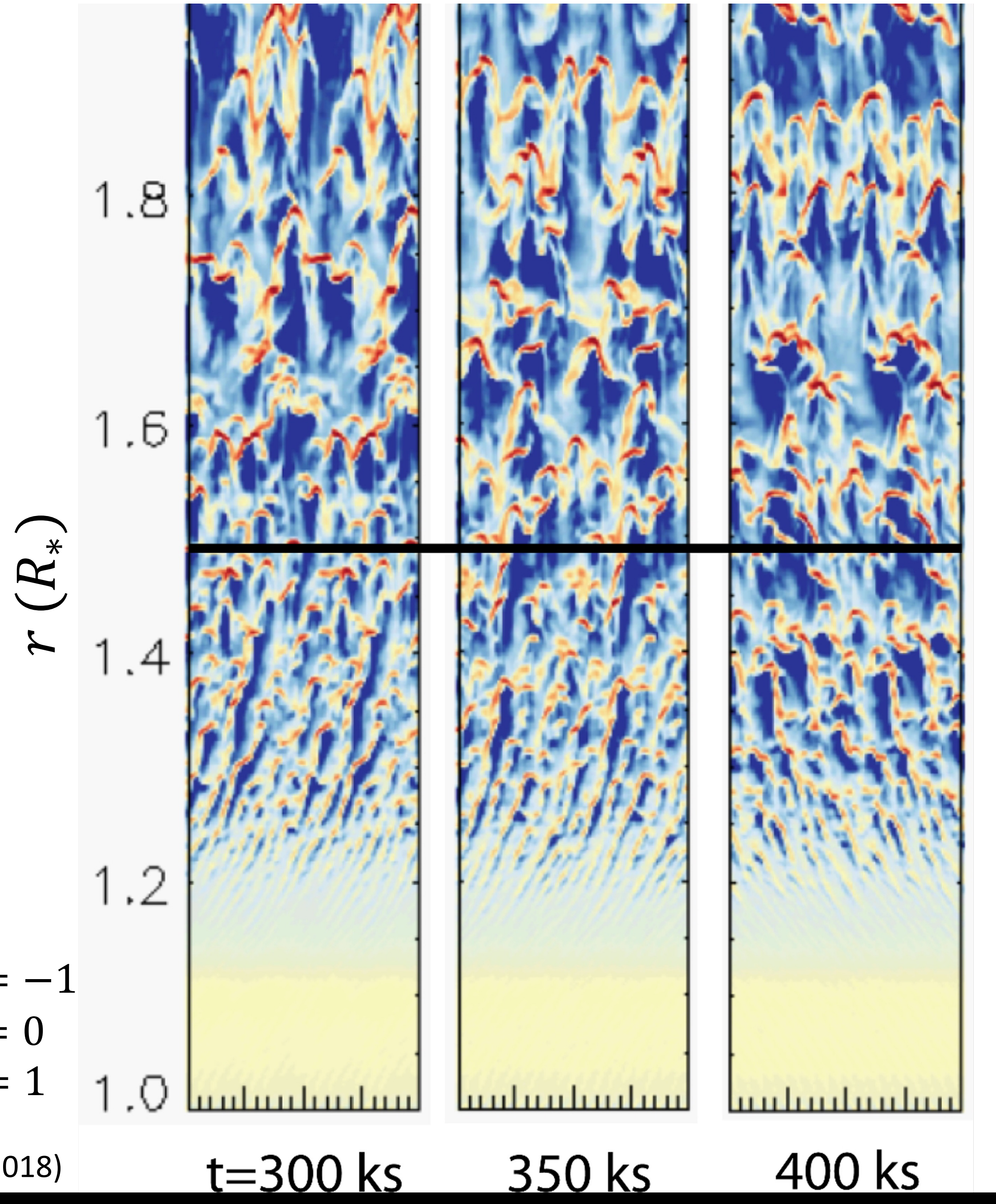
Satellite Lines: A Probe for the Plasma Conditions in Hot-Star Wind Shocks

Sean Gunderson, Kenneth Gayley, and David Huenemoerder

August 1, 2023

X-rays from Hot Stars: Embedded Wind Shocks

- Strong shocks form due to clumps experiencing different accelerations:
  - $\Delta v \sim 1000$ km/s
  - $k_B T \sim 1$ keV
- But what's the plasma state in these shocks?



Blue $\log(\rho) = -1$
Yellow $\log(\rho) = 0$
Red $\log(\rho) = 1$

Owocki & Sundqvist (2018)

IOWA

Post-Shock Plasma States

Collisional Ionization Equilibrium

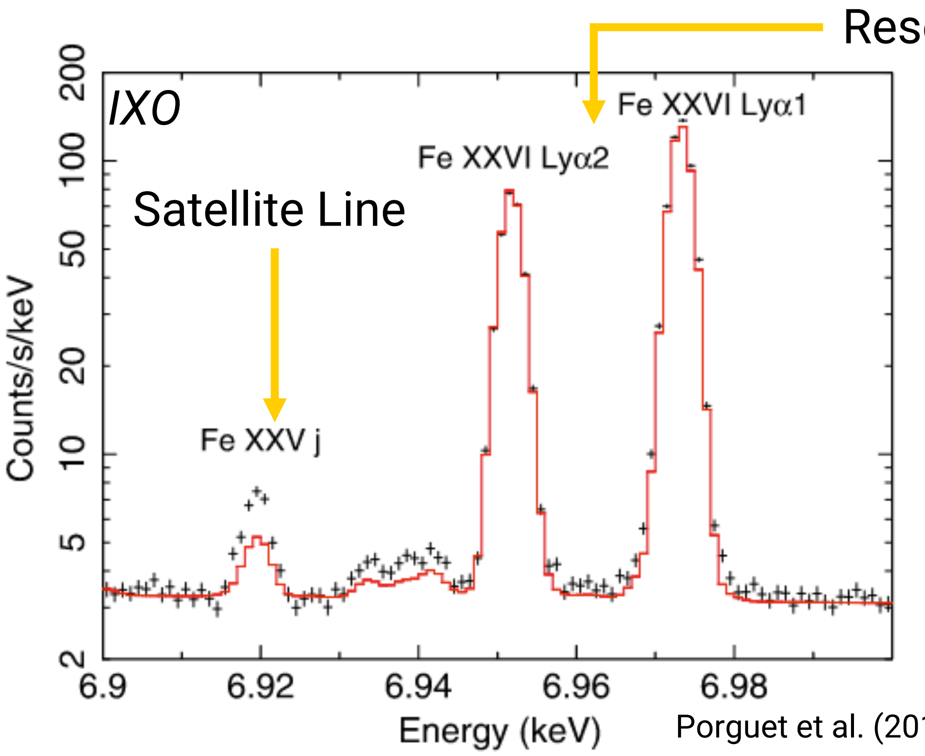
- The standard assumption/approximation
  1. It usually works
  2. Astronomical timescales allow for equilibration in shocks
- Characteristics
  1. Thermalization between species
  2. Ionizations/excitations from ion-electron collisions

Pollock's Paradigm

- Proposed in Pollock, A. M. T. (2007)
- Arguments:
  1. Length scales too long for ion-electron thermalization before quenching with cold gas
  2. No thermal background in hot star spectra
- Characteristics
  1. No hot electrons
  2. Ionizations/excitations from ion-ion collisions

Satellite Lines and Dielectronic Recombination

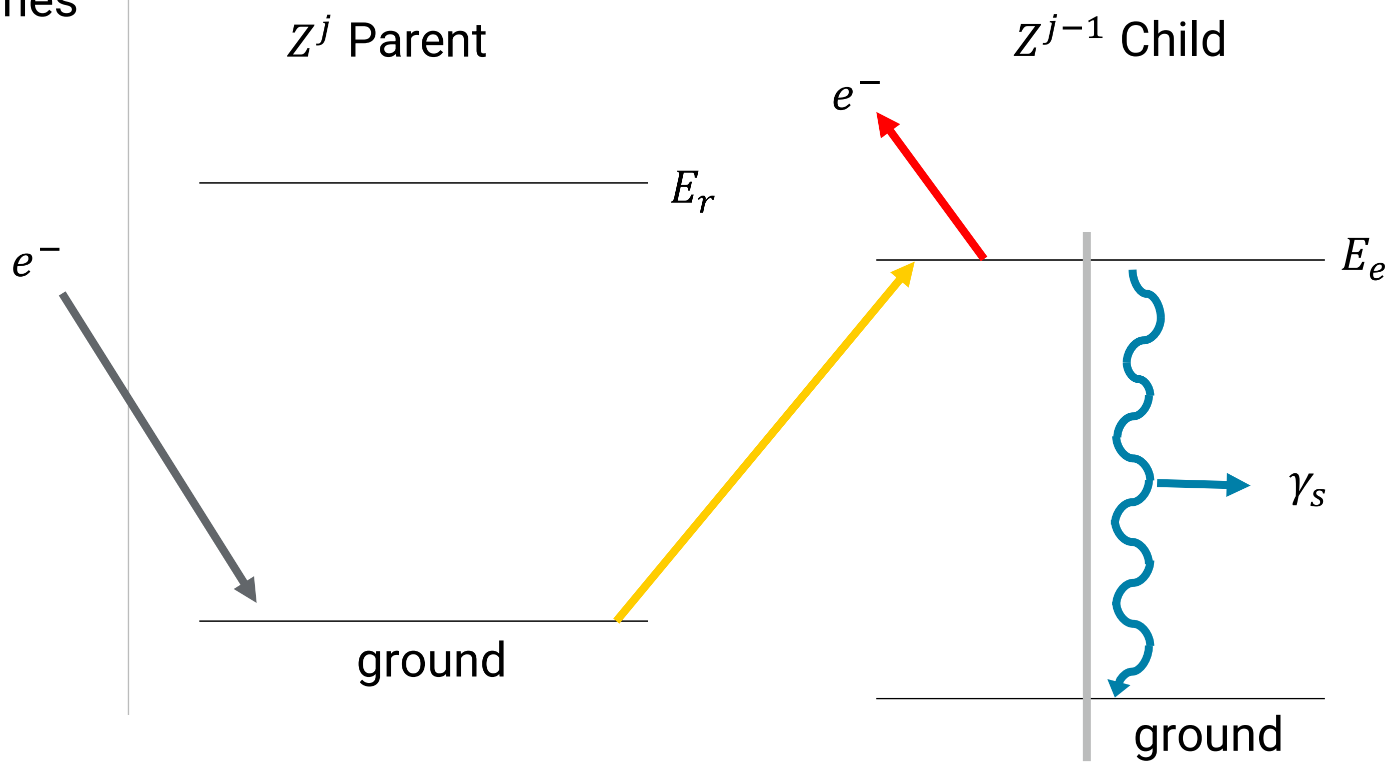
Transitions in Z^{j-1} ions that are similar to Z^{j} resonance lines but always at a lower energy



Porguet et al. (2010)

Dielectronic Recombination (DR)

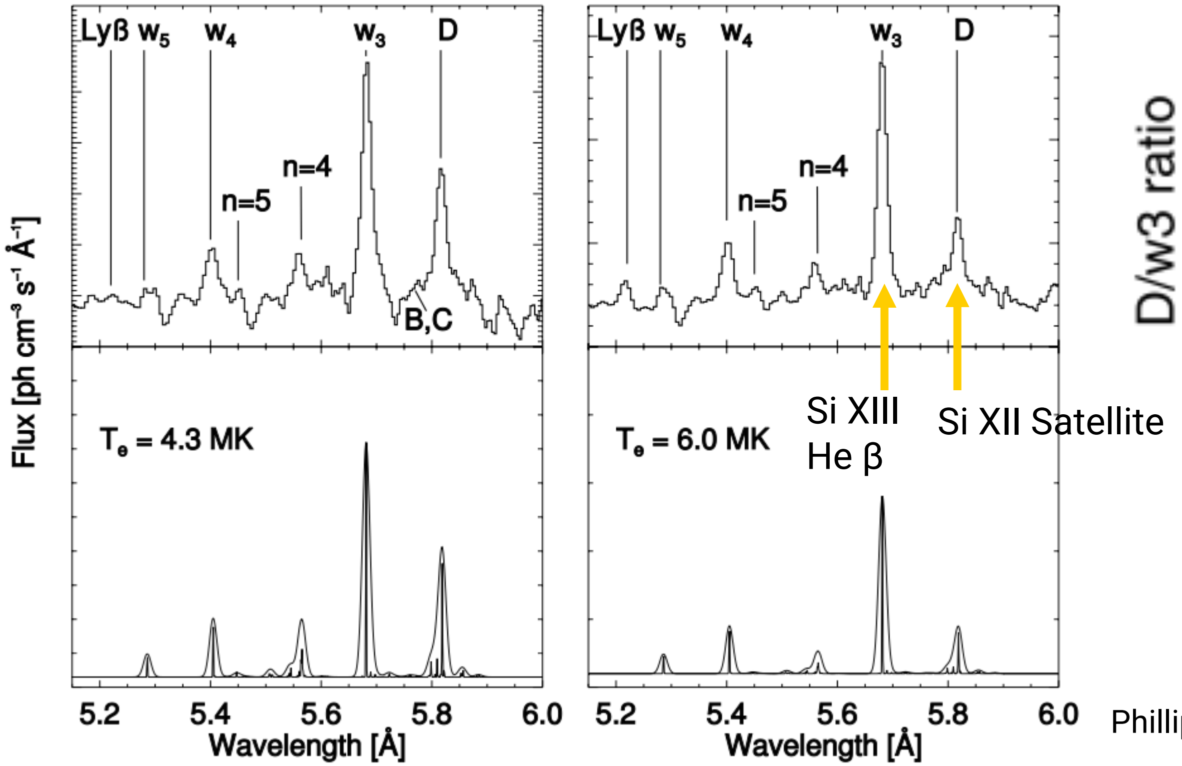
$$Z^{j} + e^{-} \Leftrightarrow Z^{(j-1)^{**}} \rightarrow Z^{(j-1)^{*}} + \gamma_s$$

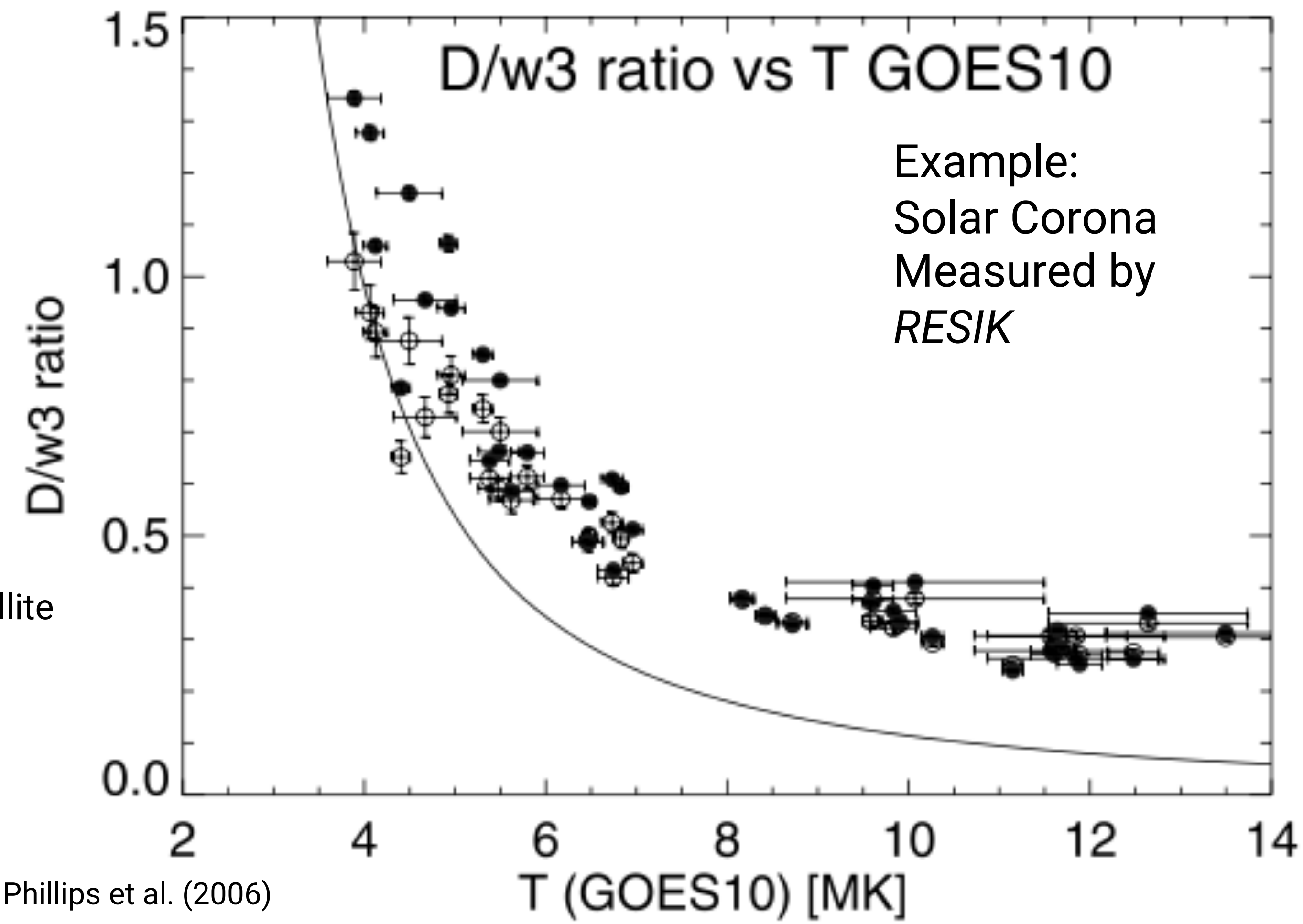


Satellite Lines as Plasma Diagnostics

$$H \equiv \frac{\mathcal{F}_s}{\mathcal{F}_r}$$

- Isothermal case
  - $H = \frac{I_s}{I_r} = K \frac{E_r}{k_B T_e} \exp\left(\frac{E_r - E_s}{k_B T_e}\right)$





Example:
Solar Corona
Measured by
RESIK

Phillips et al. (2006)

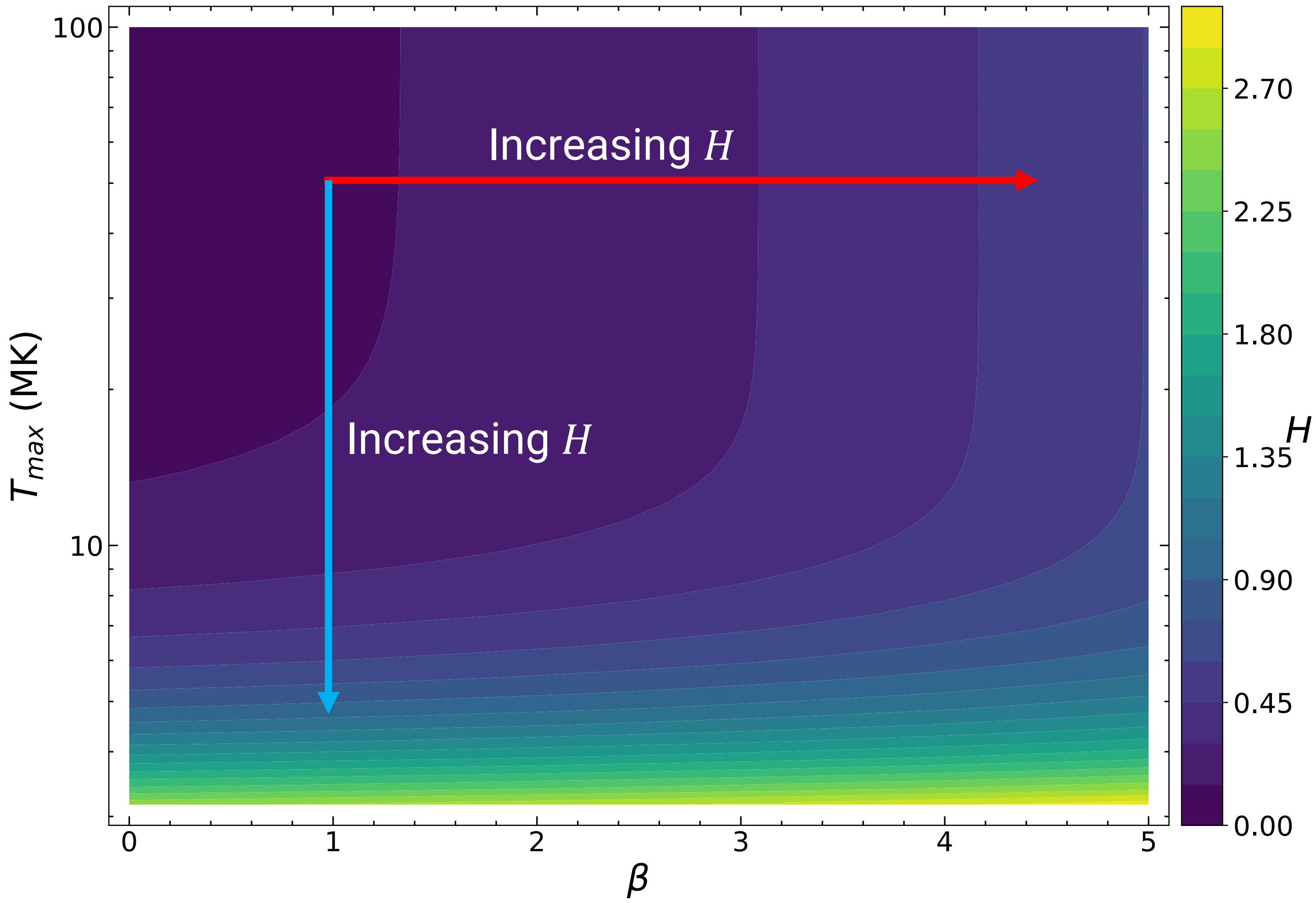
Satellite Lines as Plasma Diagnostics

$$H \equiv \frac{\mathcal{F}_s}{\mathcal{F}_r}$$

- DEM case
  - $H = \frac{\int_0^\infty \varepsilon_s(T)\mathrm{DEM}(T)\mathrm{d}T}{\int_0^\infty \varepsilon_r(T)\mathrm{DEM}(T)\mathrm{d}T}$
- $\mathrm{DEM}(T) = D_0(r)T^{-\beta}$
  - From 1 MK – T_{max}

Huenemoerder et al. (2020)

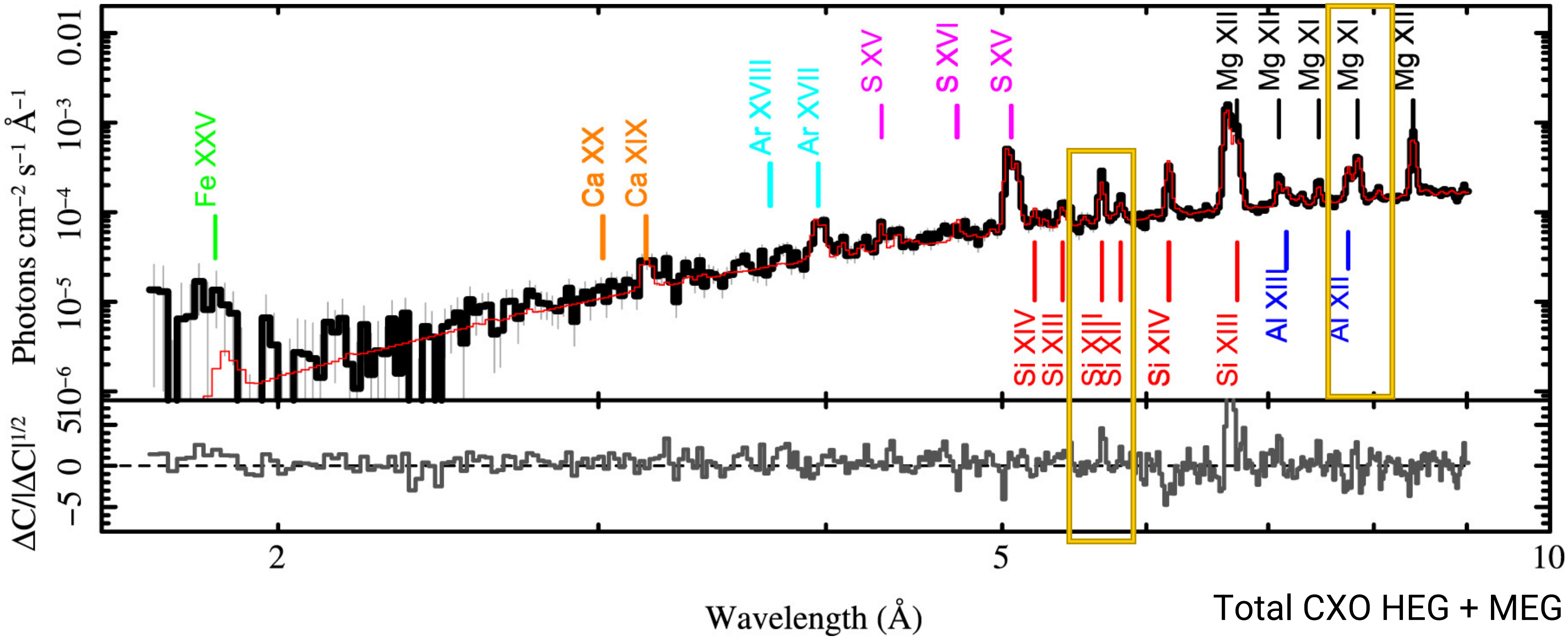
β	T_{max} (MK)
$2.6^{+0.2}_{-0.2}$	$12.02^{+0.86}_{-0.80}$



IOWA

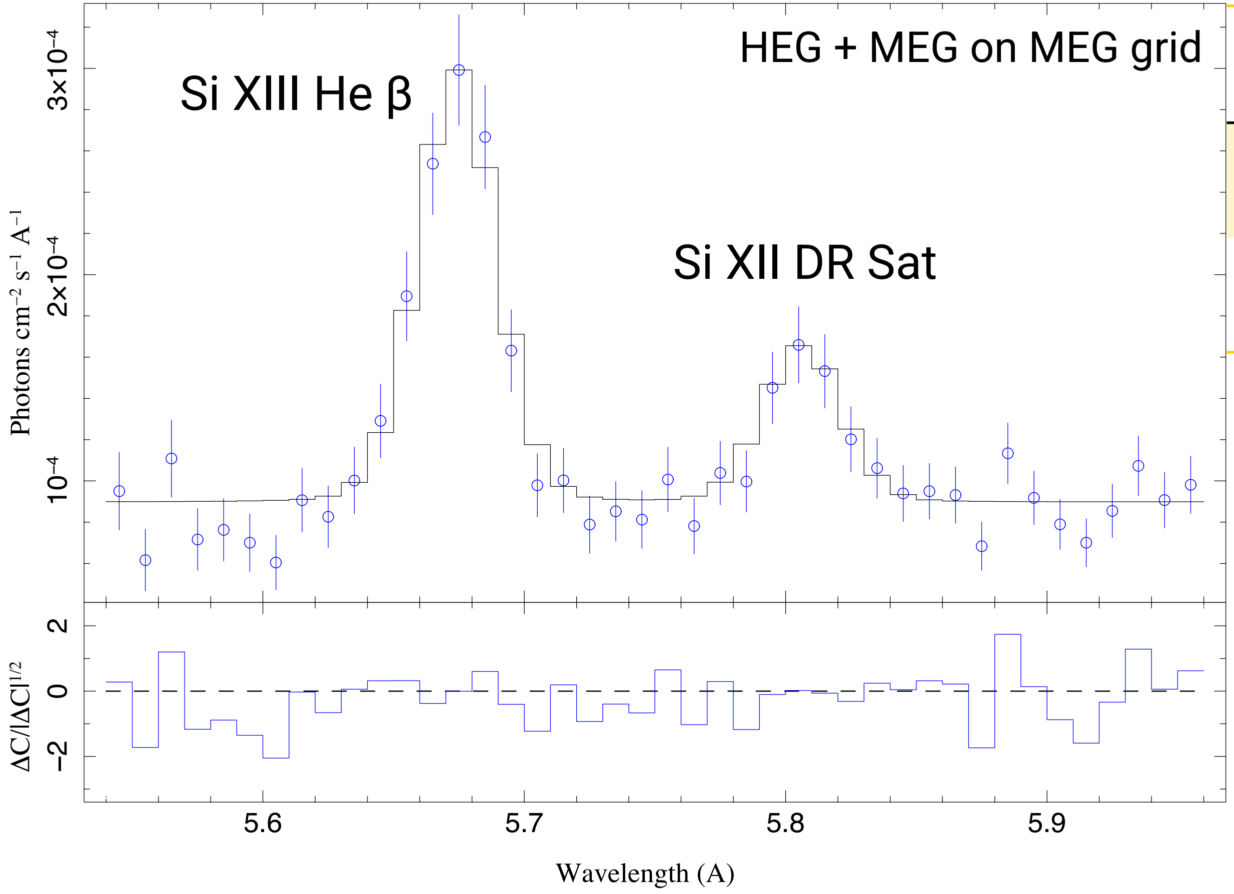
ζ Puppis – Deep Exposure: Satellite Lines

Huenemoerder et al. (2020)



Total CXO HEG + MEG

Model Fitting – The Results



Line	H_G	H_{H20}
Si XIII	$0.3620^{+0.0589}_{-0.0541}$	$0.285^{+0.0052}_{-0.0052}$
Mg XI	$0.2211^{+0.0399}_{-0.0358}$	$0.206^{+0.0063}_{-0.0063}$

- H_{H20} is not a direct measurement
  - Line fluxes are not independent parameters in the DEM model
- Best fit DEM parameters predict the observed ratio
- Evidence for CEI!

IOWA

Free Electron Temperature

$$H = K \frac{E_r}{k_B T_e} \exp\left(\frac{E_r - E_s}{k_B T_e}\right)$$

- A characteristic temperature of electrons involved in these emissions
- $T_e < T_\varepsilon$ is no surprise
  - DEM shifts the peak emission to lower temperatures
- Direct evidence of hot electrons

Temperature of maximum emissivity (from the APED) ↓ (T_ε)

Line	T_ε (MK)	T_e (MK)
Si XIII	10	$7.29^{+0.67}_{-0.55}$
Mg XI	6.31	$4.23^{+0.44}_{-0.26}$

Conclusions

1. Satellite lines provide direct evidence of hot electrons
   – Pollock's paradigm not the plasma state
   – Ion-ion collisions should be explored though!

2. Evidence of the post-shock plasma in ζ Pup's winds in CIE

3. Satellite lines can be used for massive-star wind analysis
   – Need a lot more data to see them…

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **522,** 2739–2746 (2023)
Advance Access publication 2023 April 20
https://doi.org/10.1093/mnras/stad1163

Support for the standard picture of thermal X-rays in the wind of ζ Puppis from dielectronic recombination of He-like ions

Sean J. Gunderson[1]★ Kenneth G. Gayley[1]★ and David P. Huenemoerder[2]

[1]*Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA*
[2]*Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA*

Accepted 2023 April 14. Received 2023 April 4; in original form 2023 February 14

Thermal X-rays from Dielectronic Recombination

Questions?

IOWA

Citations

Draine B. T., 2011, *Physics of the Interstellar and Intergalactic Medium*. Princeton University Press, Princeton, NJ, USA

Gabriel A. H., 1972, MNRAS, 160, 99

Gabriel A. H., Jordan C., 1969, Nature, 221, 947

Gabriel A. H., Paget T. M., 1972, J. Phys. B At. Mol. Phys., 5, 673

Gabriel A. H., Jordan C., Paget T. M.,1969, in Physics of Electronic and Atomic Collisions: ICPEAC VI. MIT, Cambridge, MA, USA, p. 558

Huenemoerder D. P. et al., 2020, ApJ, 893, 52

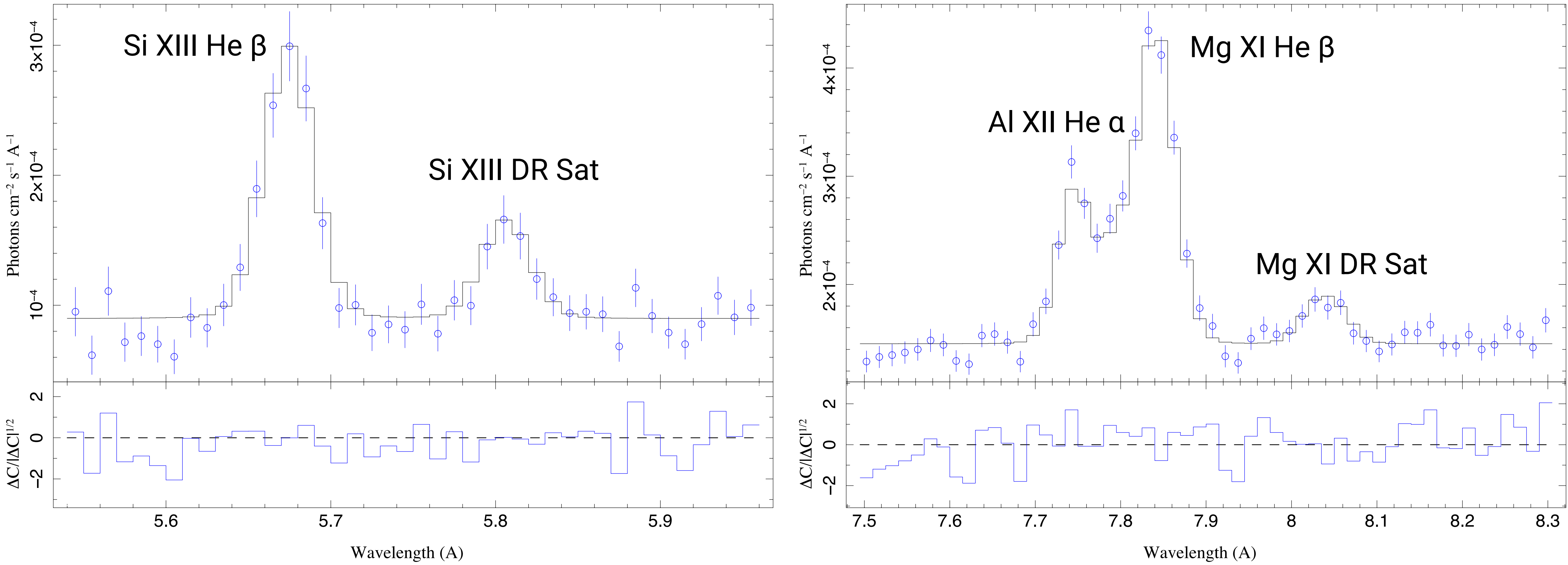
Owocki S. P., Sundqvist J. O., 2018, MNRAS, 475, 814

Pollock A. M. T., 2007, A&A, 463, 1111

Porquet D., Dubau J., Grosso N., 2010, Space Sci. Rev., 157, 103

ζ Puppis Satellite Lines – Cycle 19

HEG + MEG on MEG grid



Intensities

- DR Satellite line: $I_s(T) = n_{Zj} n_e \frac{4\pi^{3/2} a_0{}^2}{(k_B T)^{3/2}} \frac{g_s}{g_1} \frac{A_r A_a}{\sum A_a + \sum A_r} \exp\left(-\frac{E_s}{k_B T}\right)$

He-like density

- Resonance line: $I_r(T) = n_{Zj} n_e 8 \sqrt{\frac{\pi}{3}} \frac{h a_0}{m_e} \frac{f P}{E_r (k_B T)^{1/2}} \exp\left(-\frac{E_r}{k_B T}\right)$

- IE Satellite line: $I_s'(T) = n_{Zj-1} n_e 8 \sqrt{\frac{\pi}{3}} \frac{h a_0}{m_e} \frac{f_e P_e}{E_e (k_B T)^{1/2}} \exp\left(-\frac{E_e}{k_B T}\right)$

Li-like density

Temperature Formula

$$H = K \frac{E_r}{k_B T_e} \exp\left(\frac{E_r - E_s}{k_B T_e}\right)$$

$$\Rightarrow k_B T_e = \frac{E_r - E_s}{W\left(\left(1 - \frac{E_s}{E_r}\right)\frac{H}{K}\right)}$$

Lambert W-function
(aka omega function or product logarithm)