Ultraviolet Observations of Star-planet Interactions – Current Status and Future Directions

Kevin France

University of Colorado

Radio Habitability – Palm Springs

May 10th 2017

University of Colorado Boulder

LASP

Star-Planet Interactions: the effects are usually larger on the planets!

•**<u>Overview of this talk:</u>**

•Influences on the planets (thermal, ionization, photochemistry)
•Influences on the stars (magnetic, tidal)

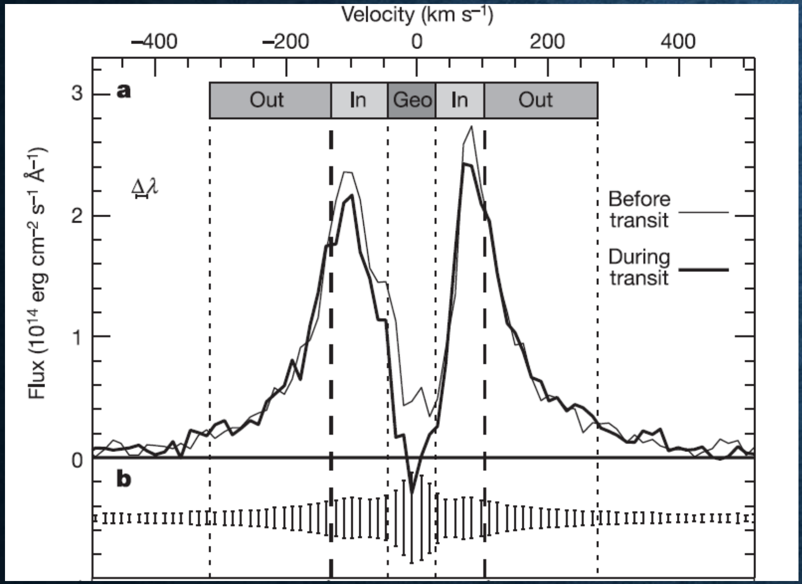
•Interactions between stellar wind/corona and the planetary magnetic field

•<u>Observations</u>:
- •UV transit spectroscopy
- •UV stellar emission lines

Future:
- •Exoplanet aurorae
- •Atmospheric loss in IR observations

FUV Transit Spectroscopy of Short-period Planets

- **EUV heating driving mass-loss from short-period planets**
- Extended hydrogen cloud indicates Roche lobe overfill and hydrodynamic atmospheric escape



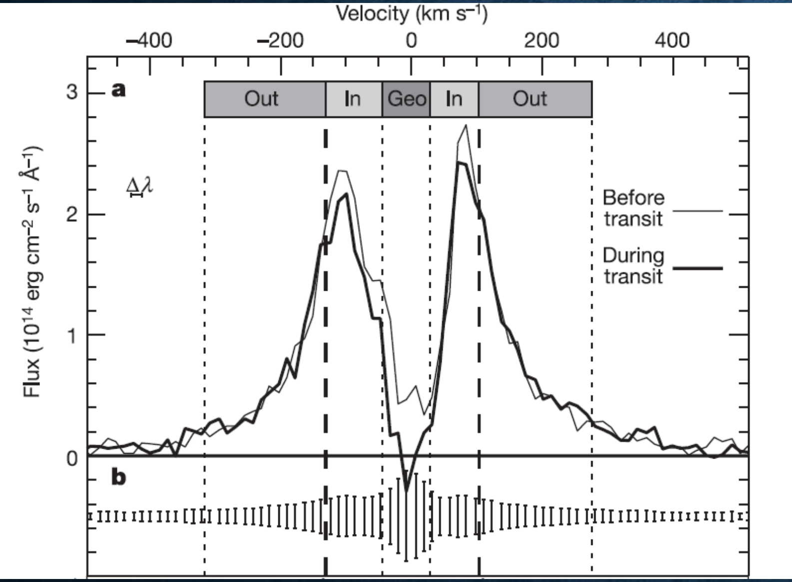
Hydrogen detected in the upper atmosphere of HD209458b (Vidal-Madjar 2003)

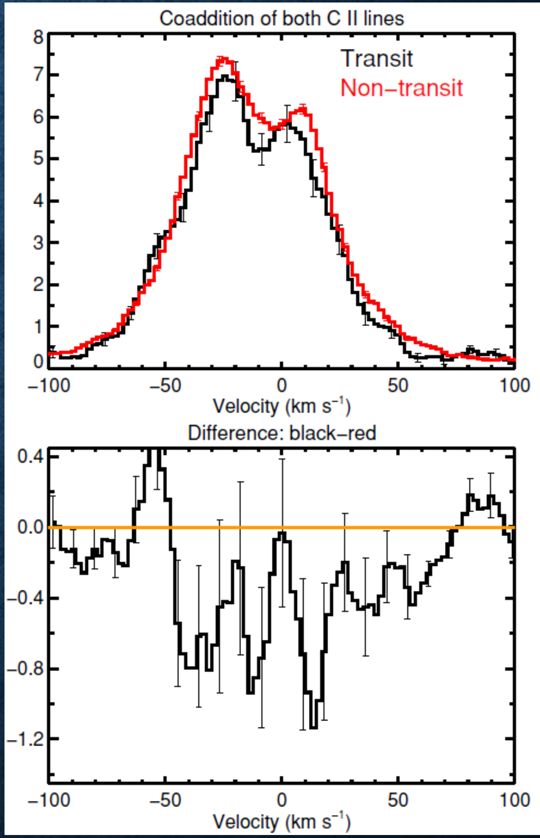
Transit depth ~ 10%
~3 - 5 × planet's geometric occultation

(Vidal-Madjar et al. 2003, 2004; Linsky et al. 2010; Lecavelier des Etanges et al. 2012; Kulow et al. 2014; Ehrenreich et al. 2015)

FUV Transit Spectroscopy of Short-period Planets

- **<u>EUV heating driving mass-loss from short-period planets</u>**
- Followed by detections of O, C, Mg, and (maybe) Si atoms/ions in the outflow



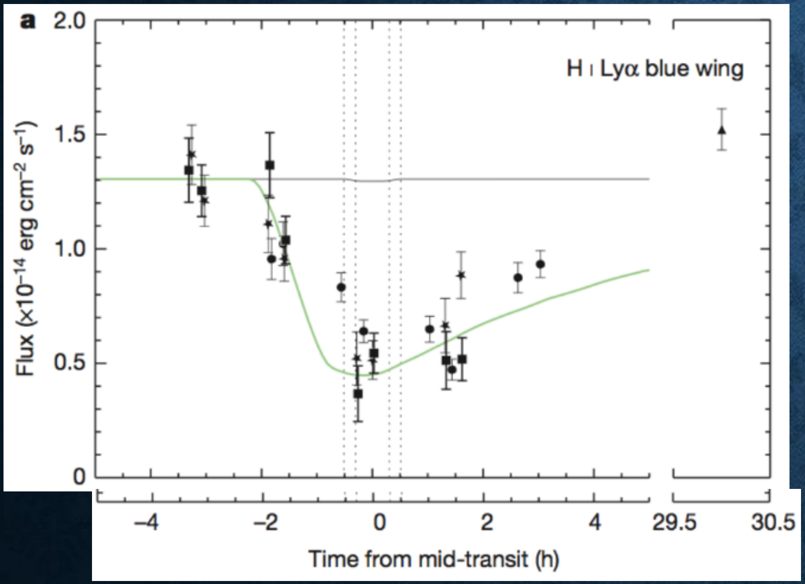


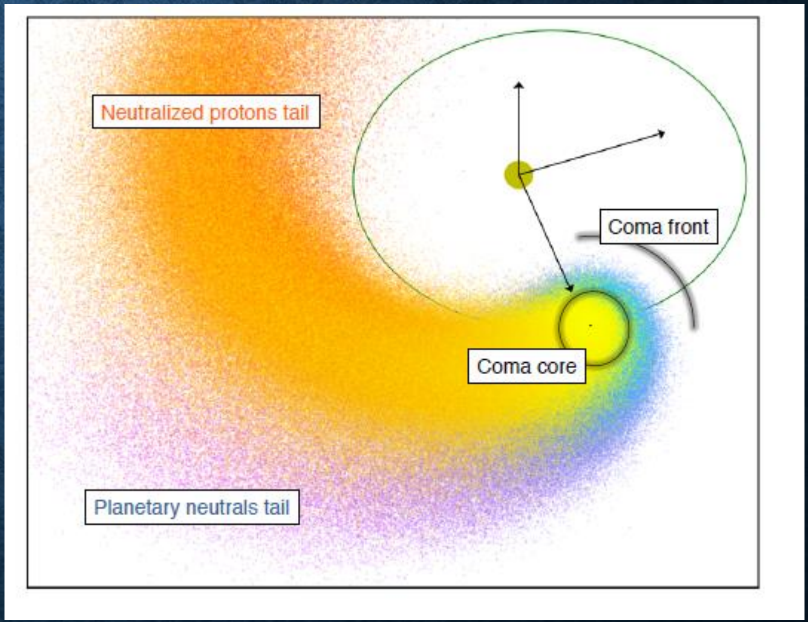
(Vidal-Madjar et al. 2003, 2004; Linsky et al. 2010; Fossati et al. 2010; Lecavelier des Etanges et al. 2012; Kulow et al. 2014; Ehrenreich et al. 2015)

Metals "dragged out", entrained in the H and He flow

FUV Transit Spectroscopy of Short-period Planets

- **<u>EUV heating driving mass-loss from short-period planets</u>**
- Most spectacular example has been on the short-period Neptune-mass planet GJ 436b





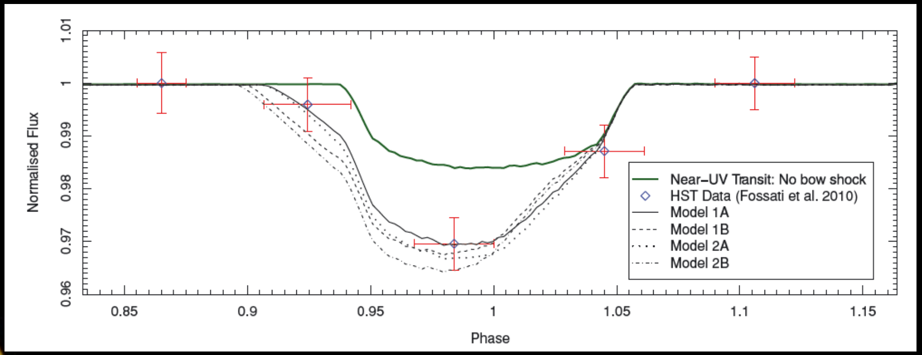
Hydrogen detected in the upper atmosphere of GJ436b (Kulow et al. 2014; Ehrenreich et al. 2015; Bourrier et al. 2016)

Transit depth ~ 50% (!)

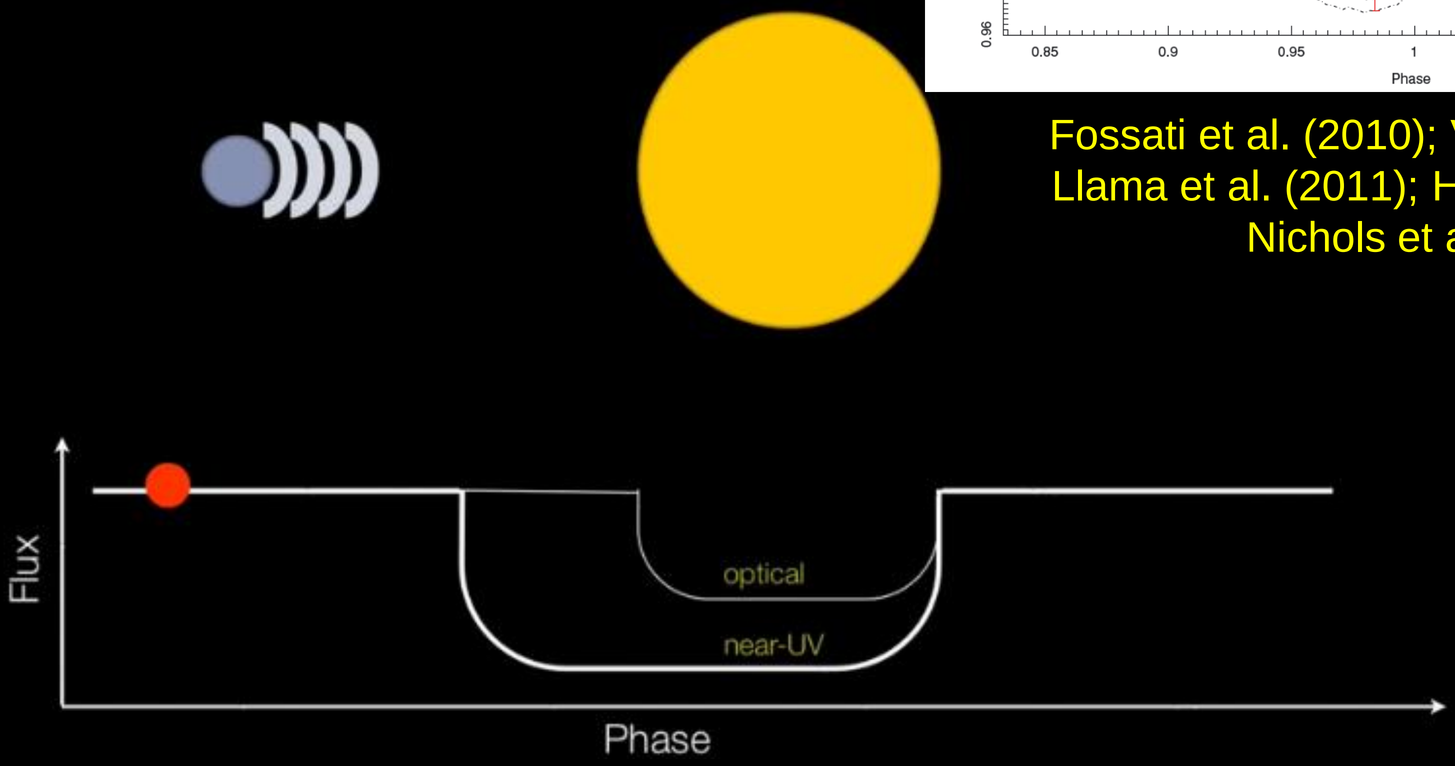
(but no metal outflow – Loyd et al. 2017)

Slide credits Joe Llama – Lowell Obs

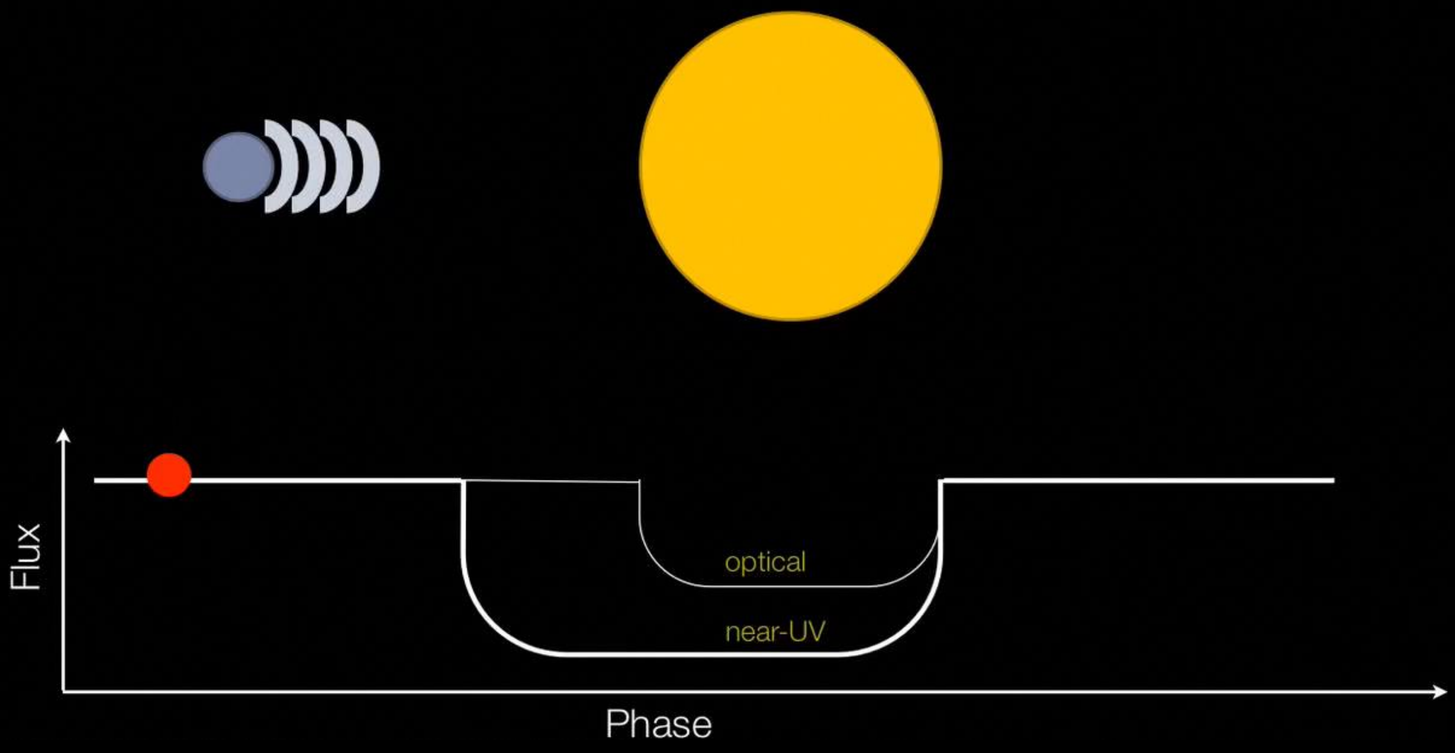
NUV Transit Spectra of WASP-12b: Early Ingress



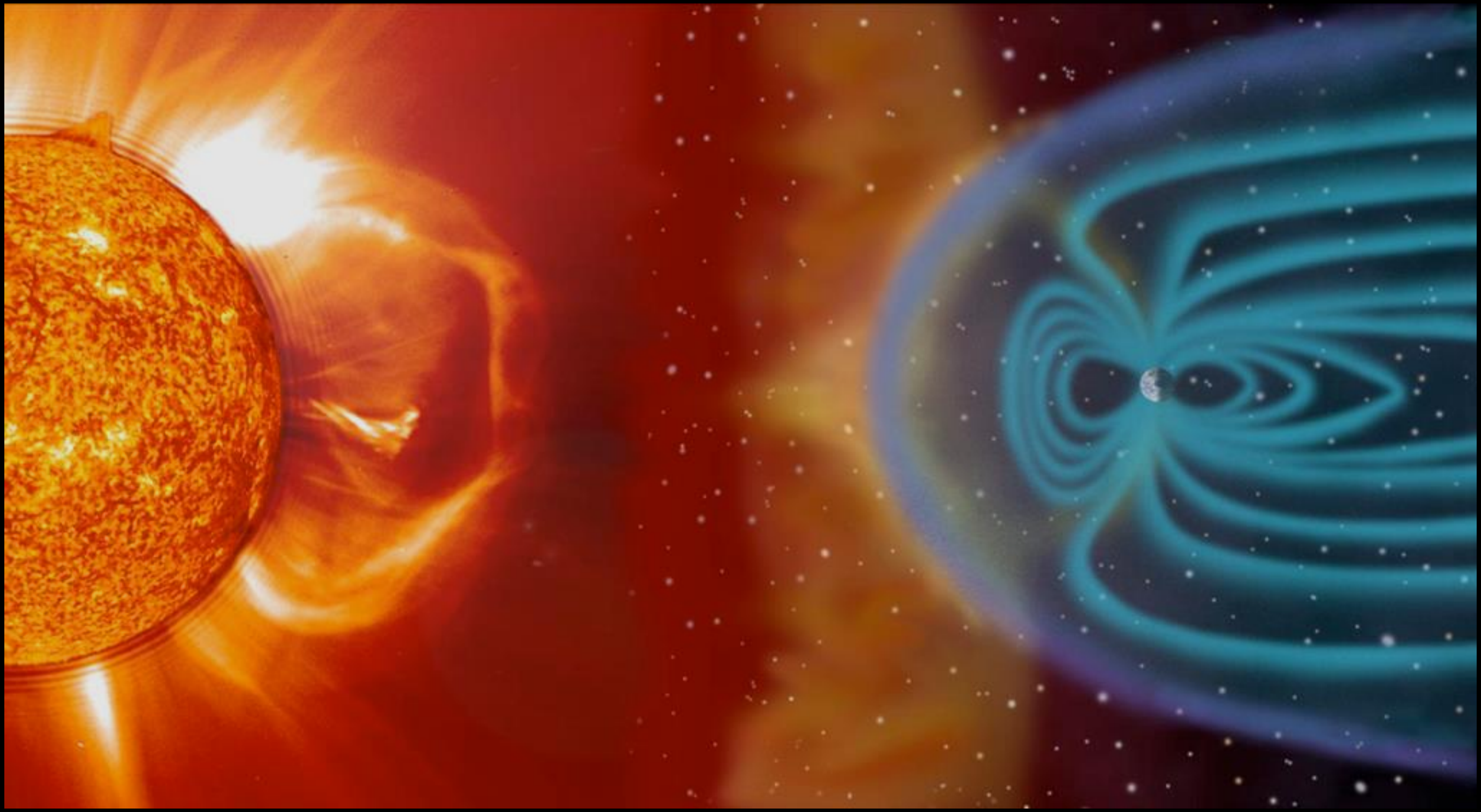
Fossati et al. (2010); Vidotto et al. (2010)
Llama et al. (2011); Haswell et al. (2012)
Nichols et al. (2015)



NUV Transit Spectra of WASP-12b: Early Ingress



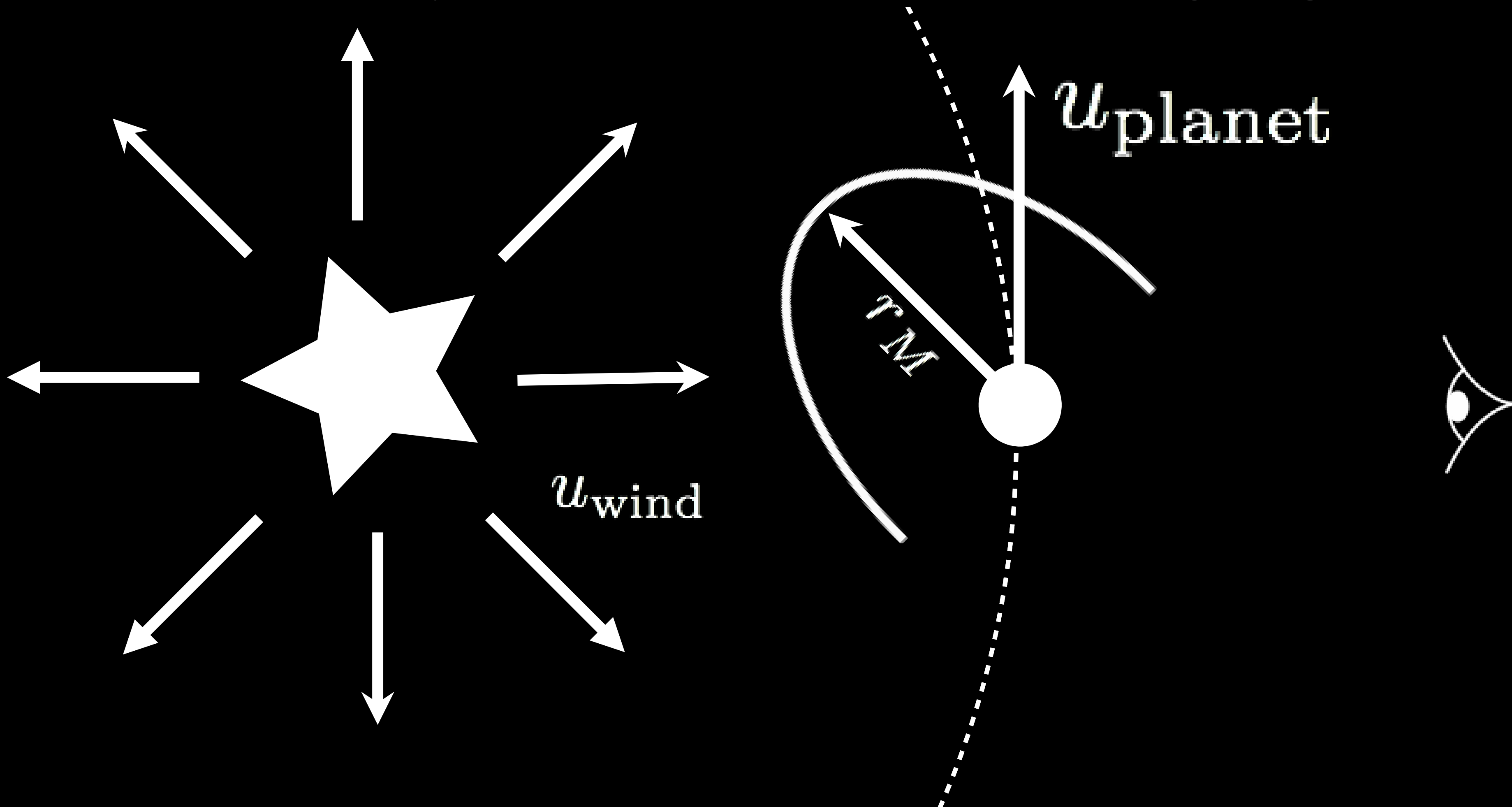
Fossati et al. (2010); Vidotto et al. (2010)



Interaction between stellar wind and planetary magnetic field may cause compression. (Vidotto et al. 2010, 2011)

Interaction strength depends on relative velocity and coronal/wind density and temperature

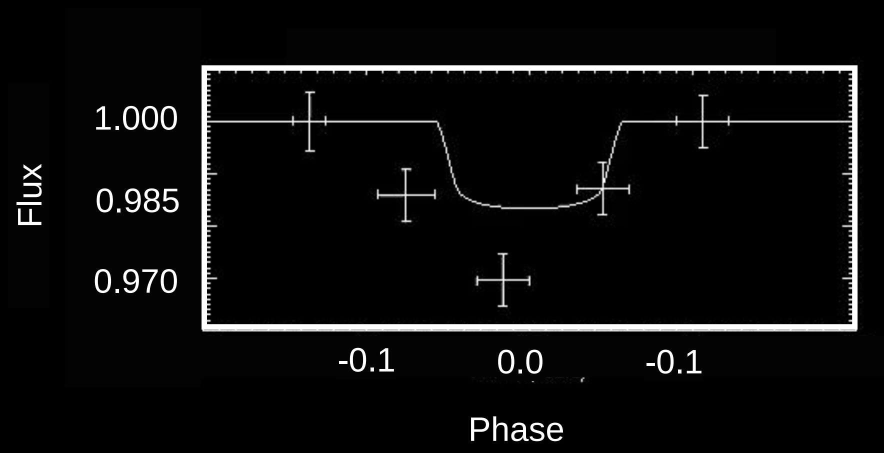
NUV Transit Spectra of WASP-12b: Early Ingress

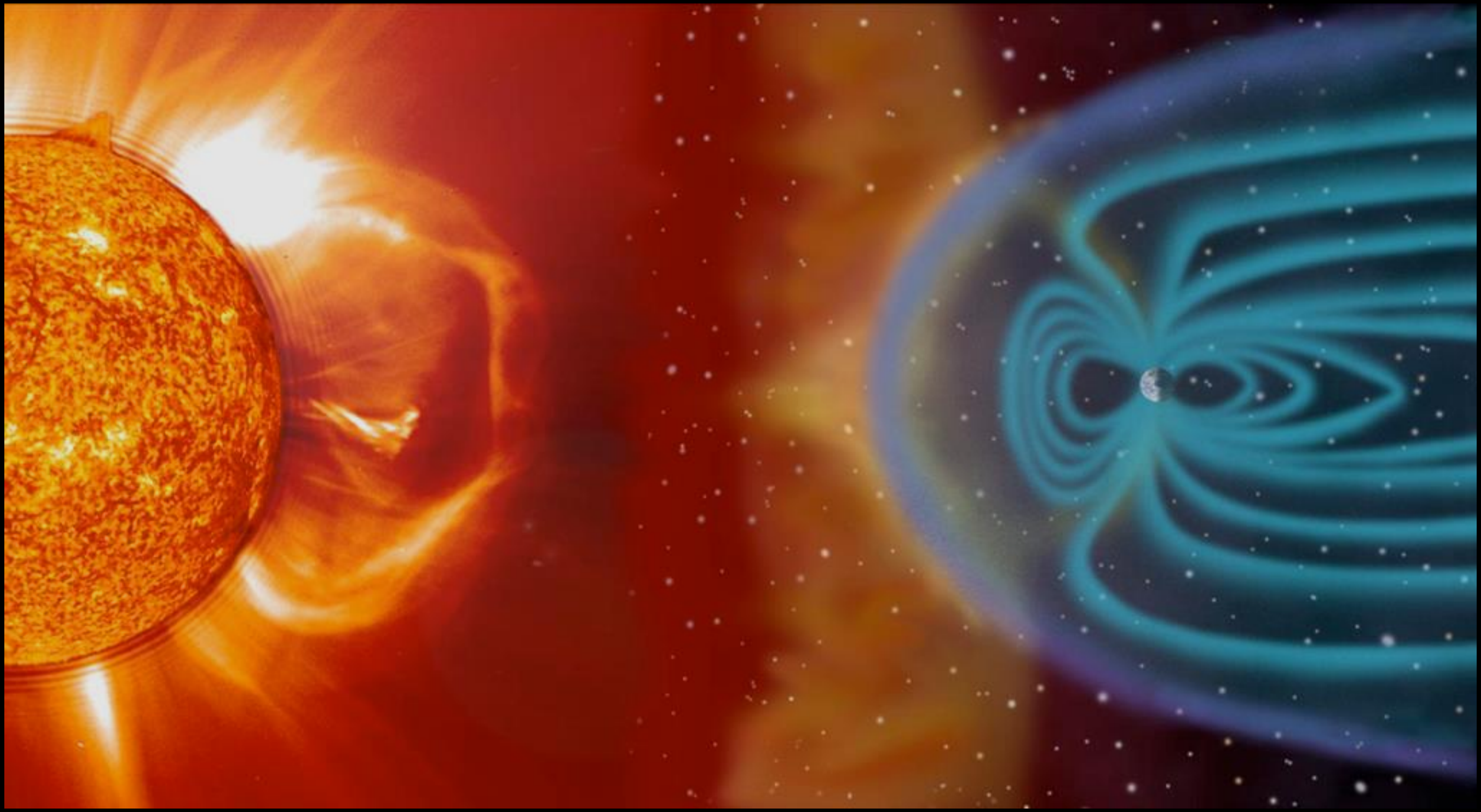


$$B_{\text{planet}}(r_M) = \frac{B_*}{2} \left(\frac{R_{\text{planet}}}{r_M}\right)^3$$

NUV Transit Spectra of WASP-12b: Early Ingress

- **Llama et al. (2011):**
    - Potential detection of a magnetic field around WASP-12b.
    - Magnetosphere protects the atmosphere to ~5 Rp.
    - Bp ~ 24 Gauss





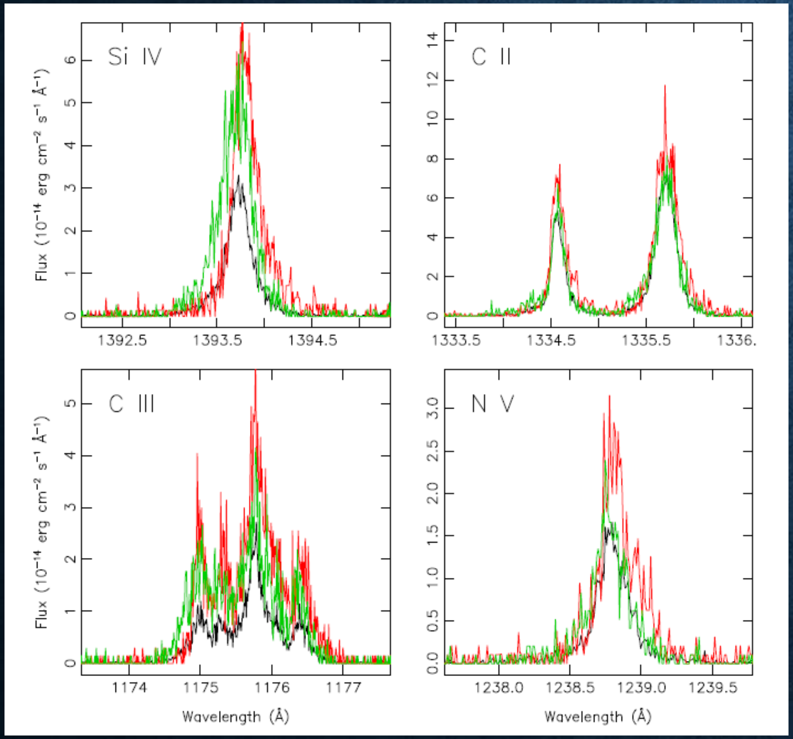
Not the only interpretation:

- Hydrodynamic mass-loss may support an upstream shock (Lai et al. 2010)
- Accretion stream onto the star ahead of the motion (Bisikalo et al. 2013)
- Plasma torus from satellites (Ben-Jaffel & Ballester 2014; Kislyakova et al. 2016)
- CLOUDY modeling finds compressed stellar winds produce insufficient optical depth, arguing for the planetary mass-loss explanation (Turner et al. 2016)

MAGNETIC ENHANCEMENTS ON THE STAR

MAGNETIC ENHANCEMENTS ON THE STAR

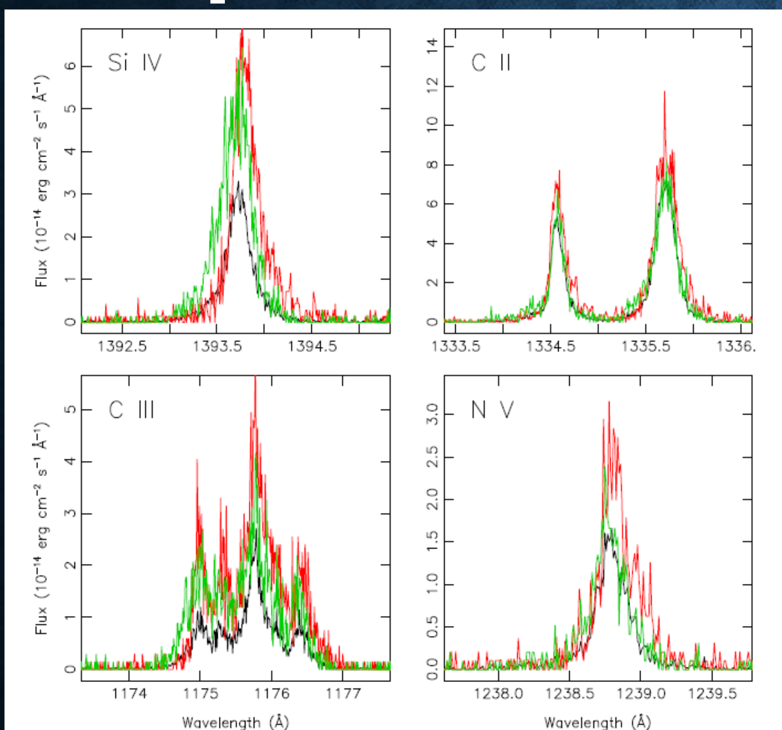
- **Magnetospheric accretion from HD 189733b?**
  - HST-COS FUV chromospheric and transition region lines on HD189733
  - Phase-dependent variability

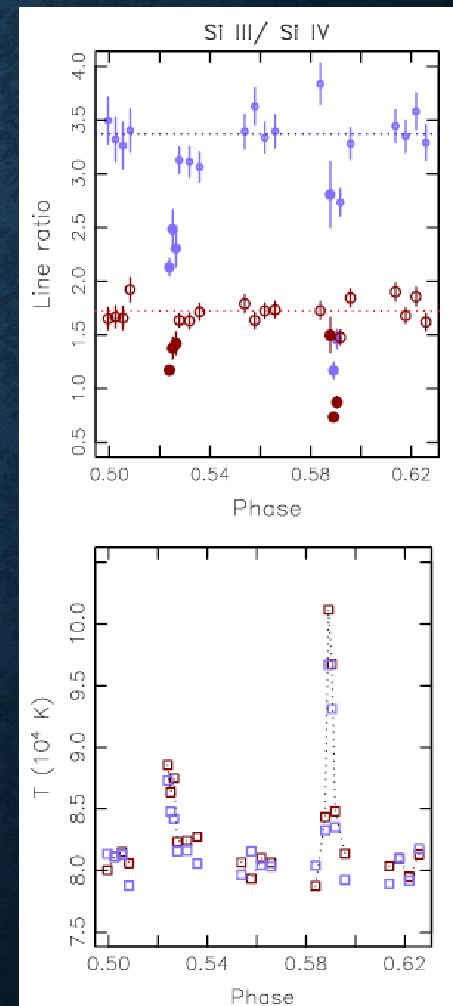


Pillitteri et al. (2015)

MAGNETIC ENHANCEMENTS ON THE STAR

- **Magnetospheric accretion from HD 189733b?**
  - HST-COS FUV chromospheric and TR lines
  - Phase-dependent variability
  - Temperature variation in outbursts

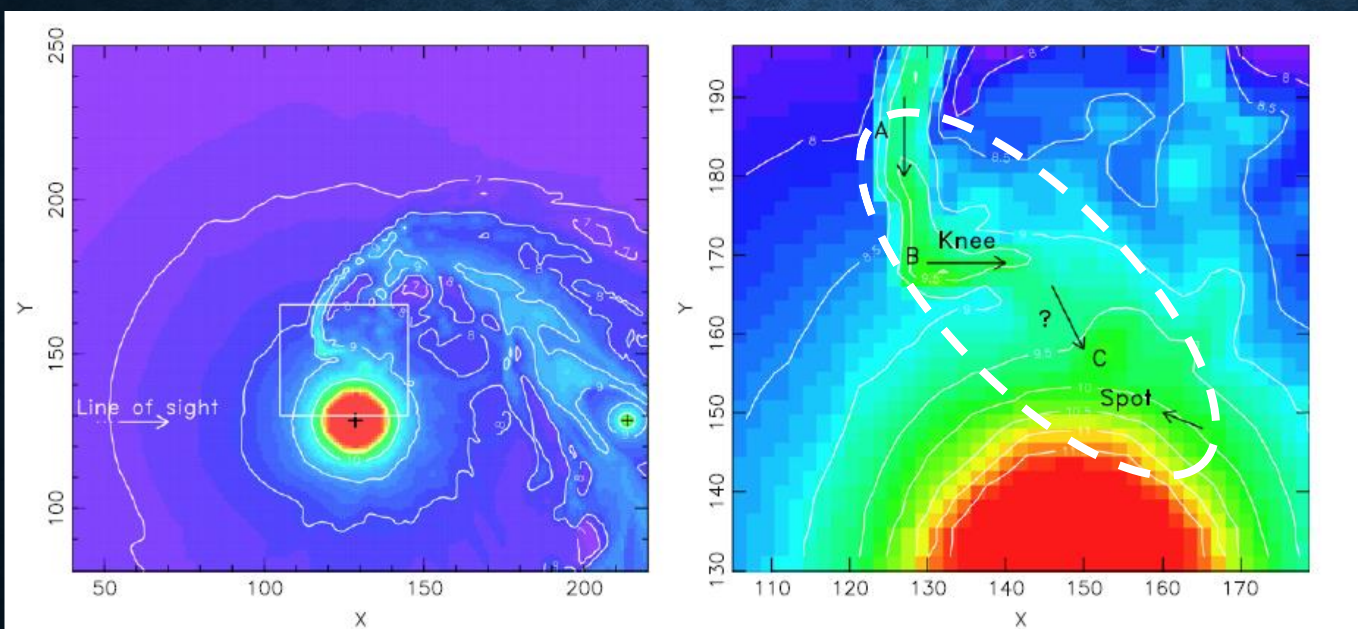


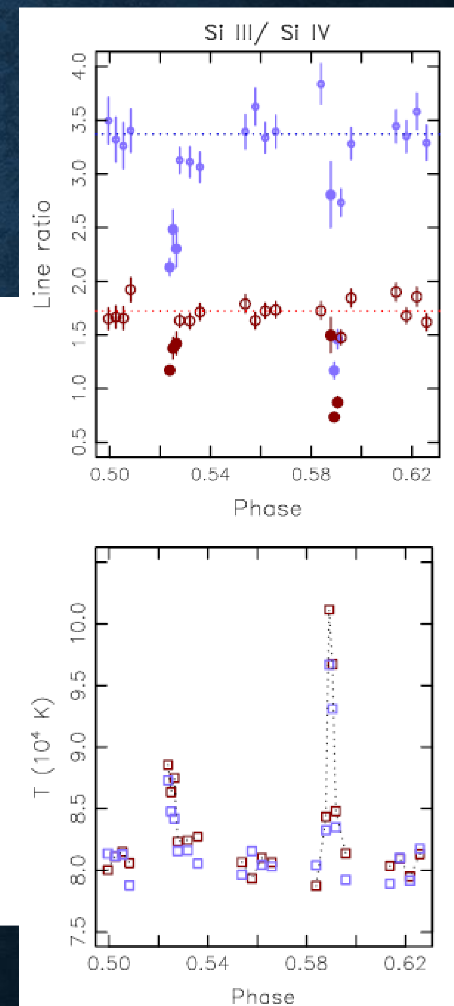


Pillitteri et al. (2015)

MAGNETIC ENHANCEMENTS ON THE STAR

- **Magnetospheric accretion from HD 189733b?**
  - Phase-dependent variability
  - Shocked planetary material accreted into stellar atmosphere ahead of orbital motion
  - *Similar flare levels seen at other phases*





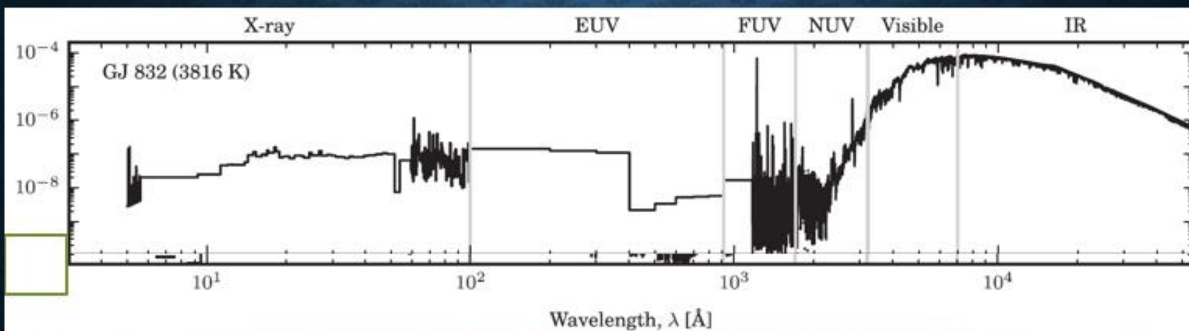
Pillitteri et al. (2015), Haswell et al. (2012)

MUSCLES: LOW-MASS EXOPLANET HOST STAR SURVEY

HTTPS://ARCHIVE.STSCI.EDU/PREPDS/MUSCLES/

X-RAY (5 Å) → IR (5 MICRON) STELLAR IRRADIANCES

Loyd et al. (ApJ – 2016)

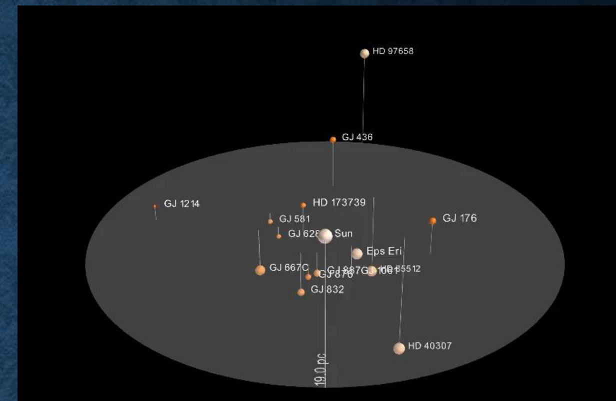


Chandra/XMM

France et al. (ApJ-2016): overview
Loyd et al. (ApJ-2016): catalog
Youngblood et al. (ApJ-2016): Lyα and EUV

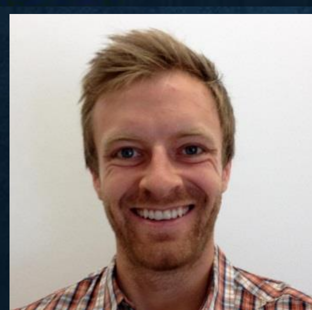
Hubble

Loyd et al. (ApJ-2017): flares and photochemistry
Youngblood et al. (ApJ-2017): UV-to-optical & CMEs



PI – France

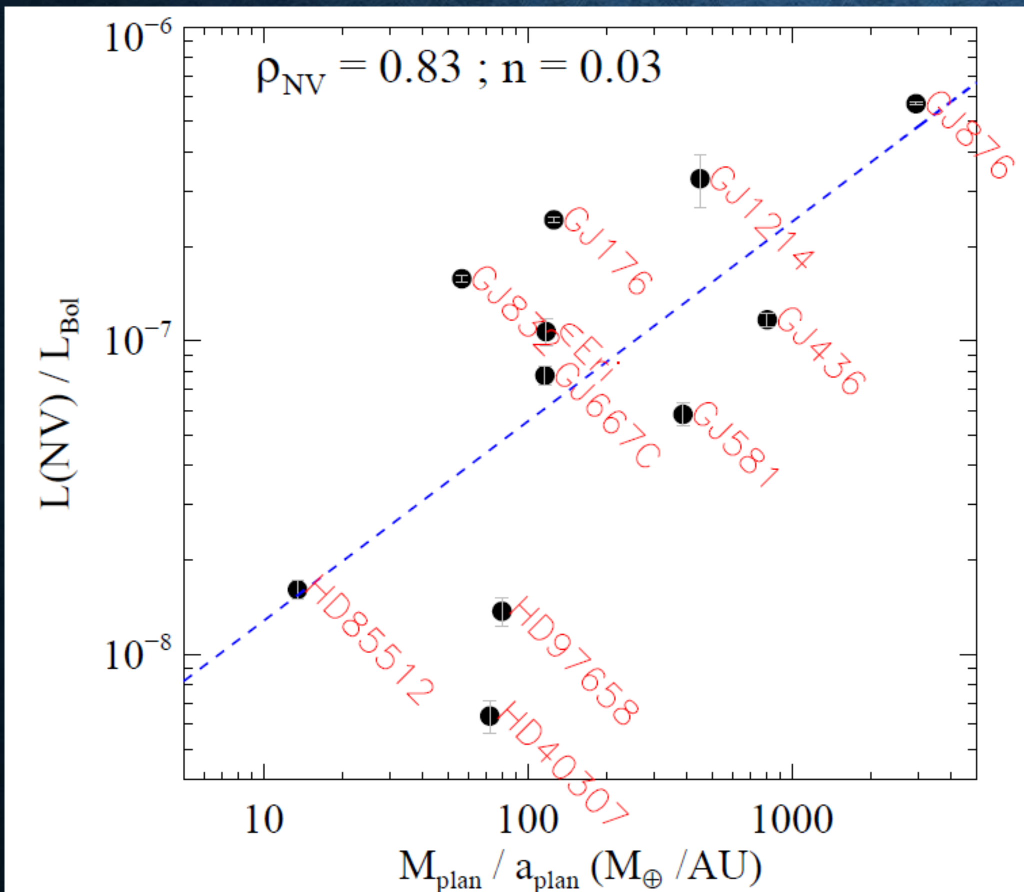
Allison Youngblood



Parke Loyd

Measurements of the
Ultraviolet
Spectral
Characteristics of
Low-mass
Exoplanetary
Systems

MAGNETIC ENHANCEMENTS ON THE STAR



France et al. (ApJ-2016)

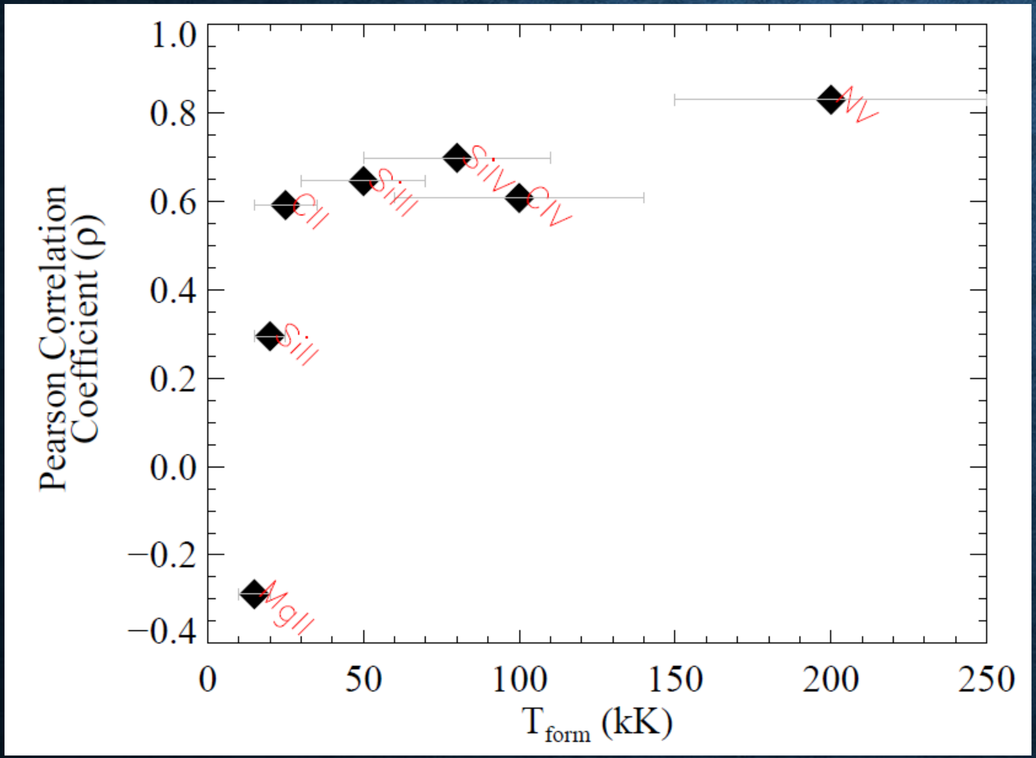
- Enhanced activity with "star-planet interaction strength"

L(line)/L_{bol} vs. M_{plan}/a_{plan}

in transition region lines

France et al. (ApJ-2016)

MAGNETIC ENHANCEMENTS ON THE STAR



France et al. (ApJ-2016)

•Enhanced activity with "star-planet interaction strength"

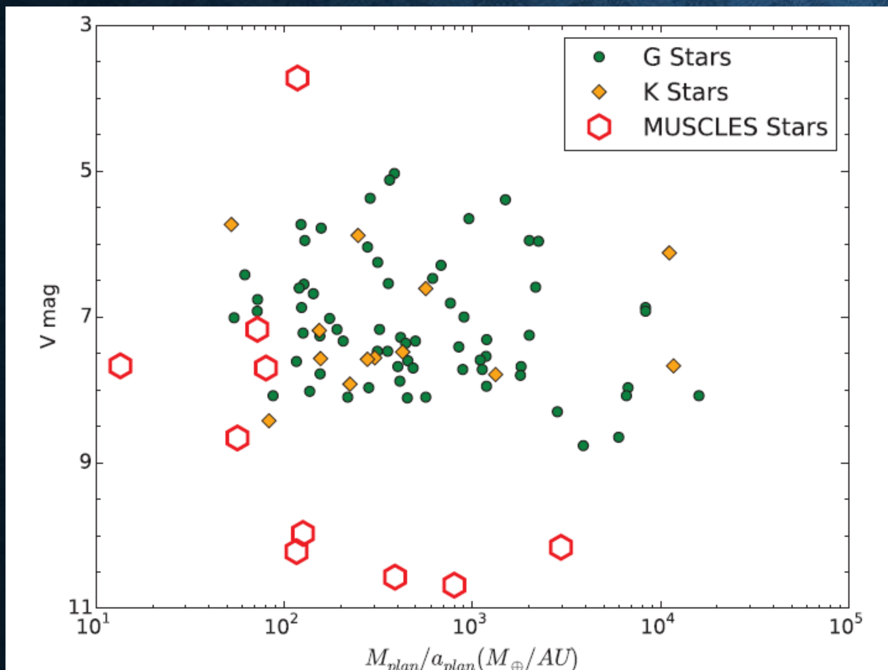
L(line)/L_{bol} vs. M_{plan}/a_{plan}

- Strong correlations only present in higher ions (T_{form} > 30,000 K)
- Suggests energy deposition occurs in transition region or coronal plasma
- More T_{eff} and planetary architectures needed!

Future Directions for UV SPI studies

- Expanding current HST surveys
- Stellar UV observations in coordination with JWST or 30m telescope spectroscopy of M dwarf rocky planets
- Exoplanetary aurorae
- Dedicated small space missions

THE FUTURE: EXPANDED HST SURVEYS



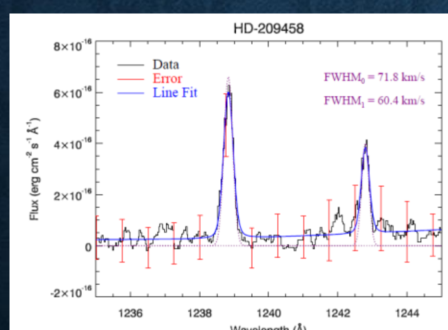
- Cycle 24 SNAP program of 80 G and K stars with known planetary system

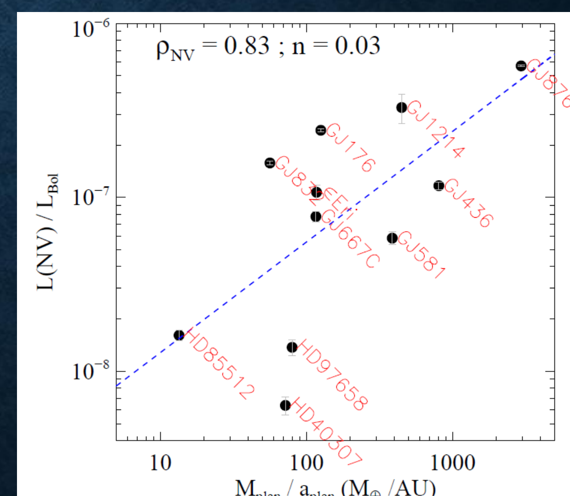
- Hubble archive control sample

Extend in M/a and T_{eff} space,
Compare with non-planet hosts

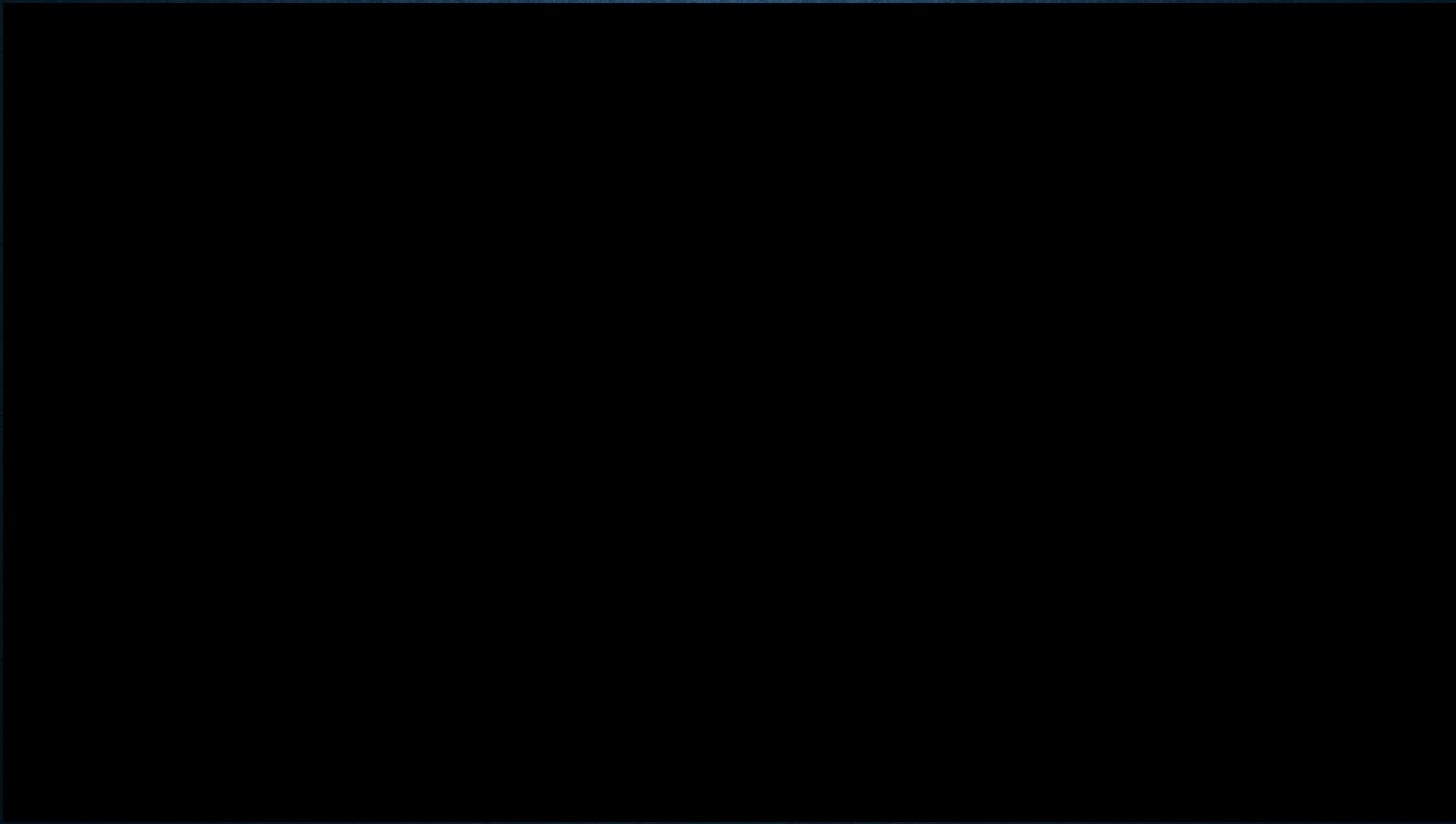
PI -

Nicole Arulanantham

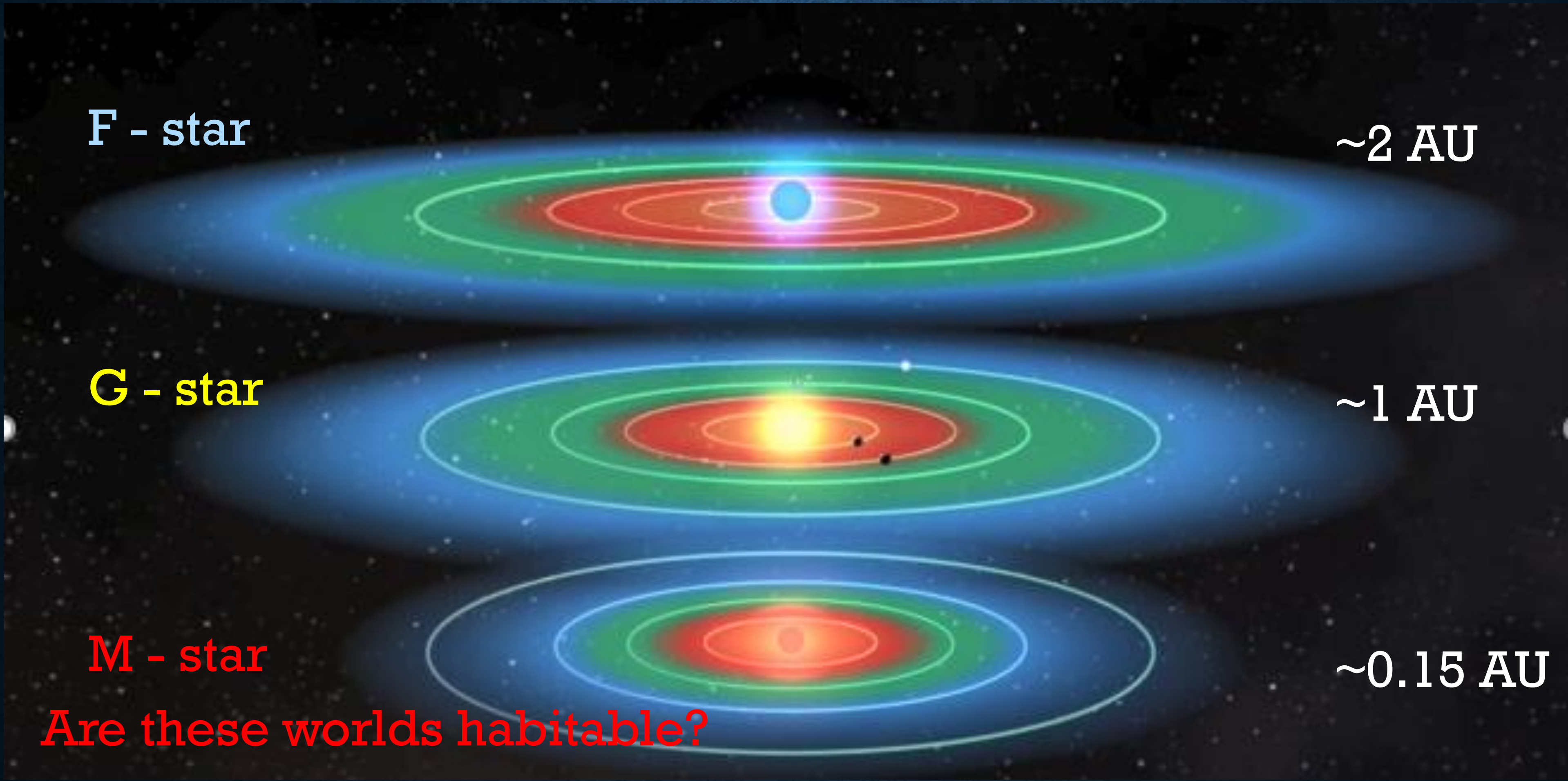




Impacts on rocky planets, coordinating with IR transit spectroscopy



Impacts on rocky planets, coordinating with vis/IR atmospheric spectroscopy

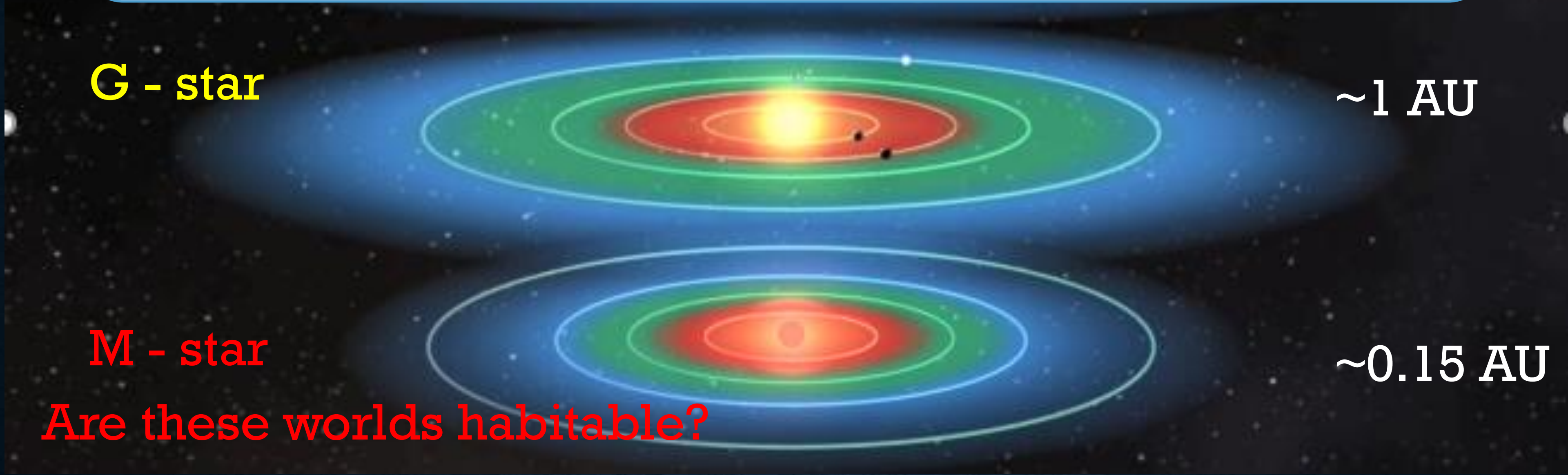


not to scale

Impacts on rocky planets, coordinating with vis/IR atmospheric spectroscopy

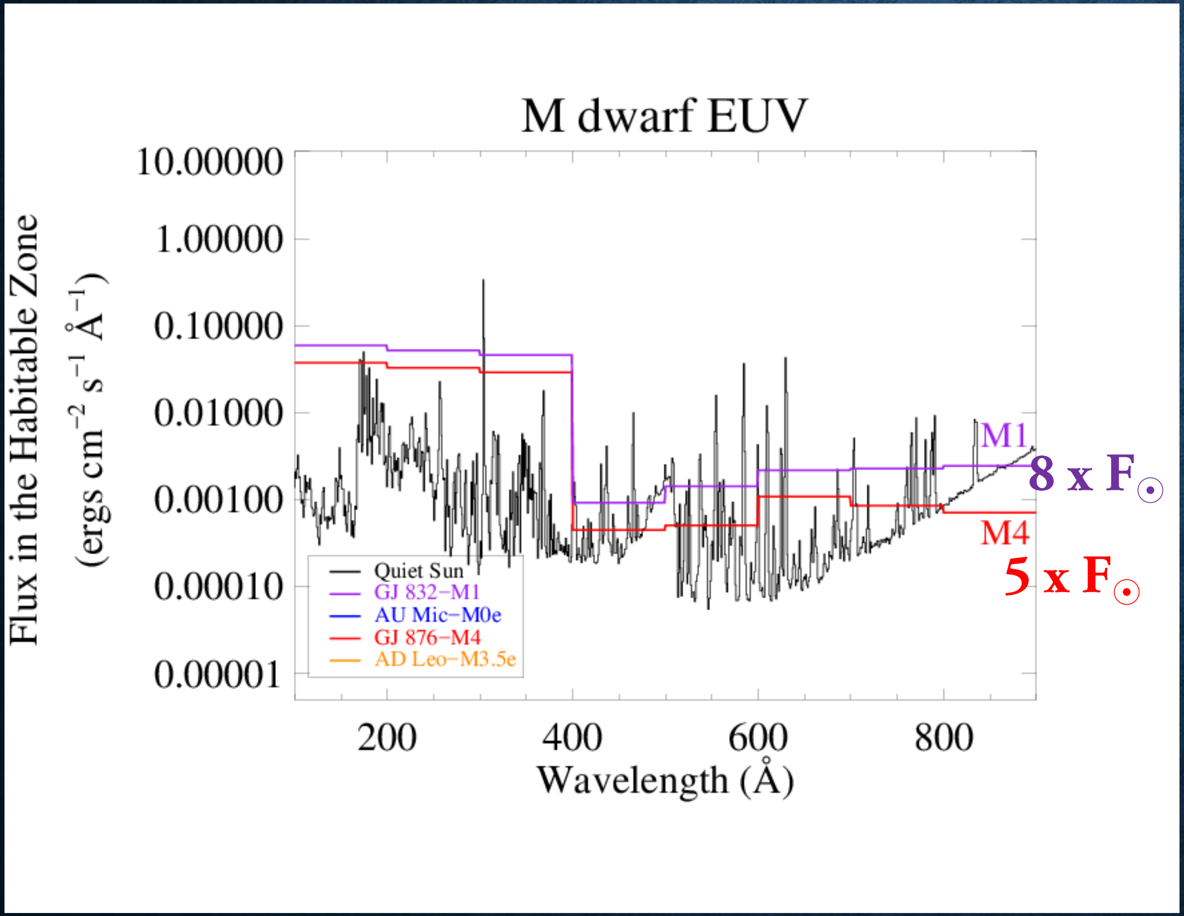
Question A: Are the atmospheres of terrestrial planets around M dwarfs stable?

Question B: How do impulsive events (flares and energetic proton events) impact the composition of a planet's atmosphere?



not to scale

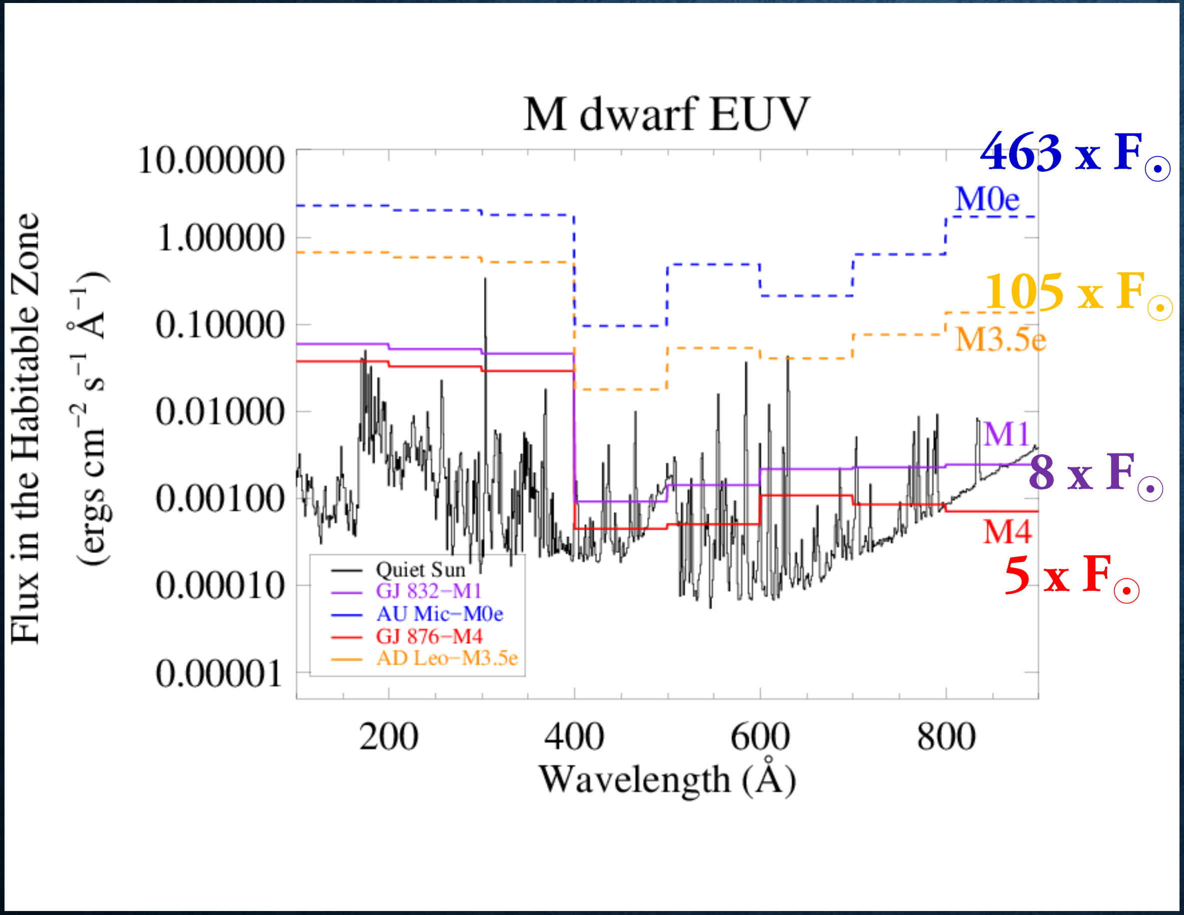
"ACTIVE" VS "INACTIVE"
M DWARFS AND ATMOSPHERIC RETENTION



F(EUV) from inactive M dwarfs 5 – 10 x larger than from the quiet Sun

M dwarf EUV: Allison Youngblood - CU

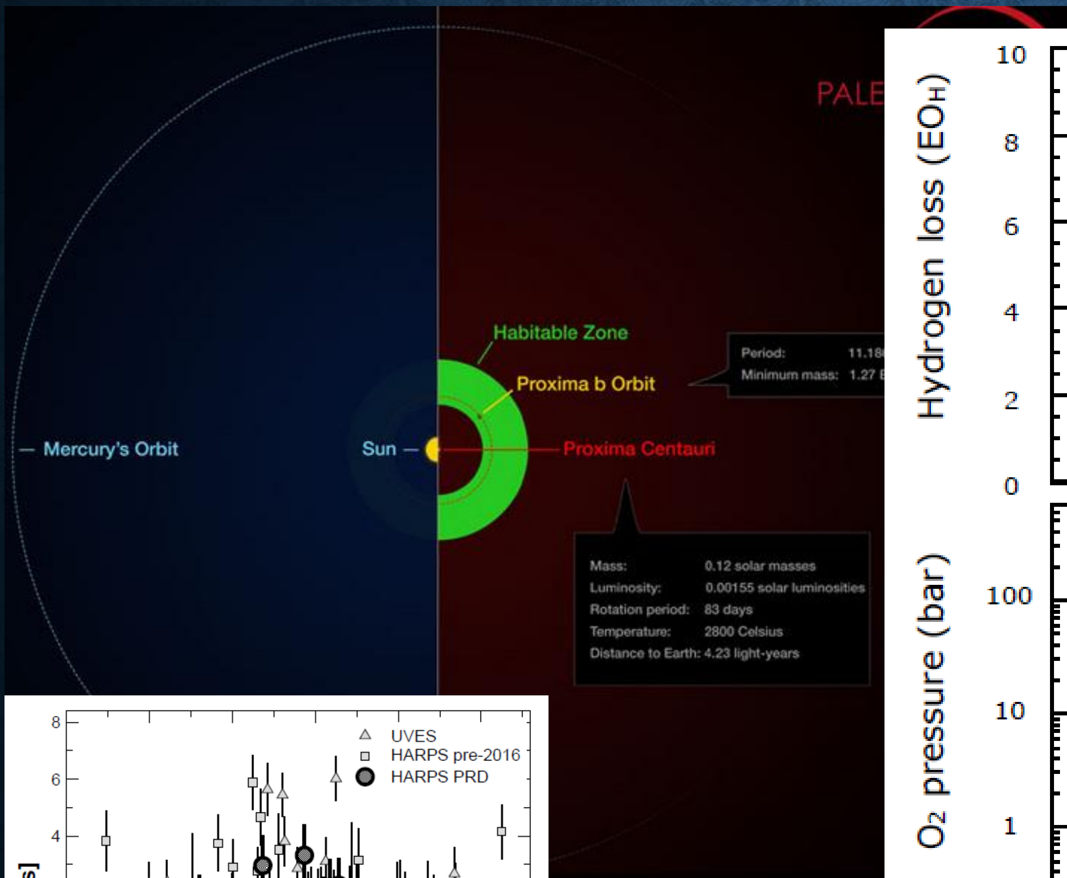
"ACTIVE" VS "INACTIVE" M DWARFS AND ATMOSPHERIC RETENTION

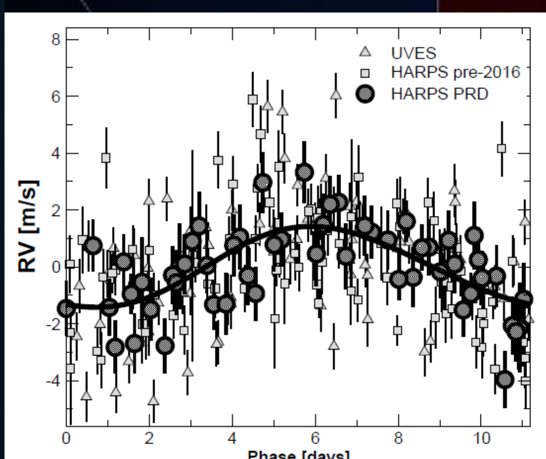


F(EUV) on an active M dwarf ~ 20 – 60x higher than on an inactive M dwarf

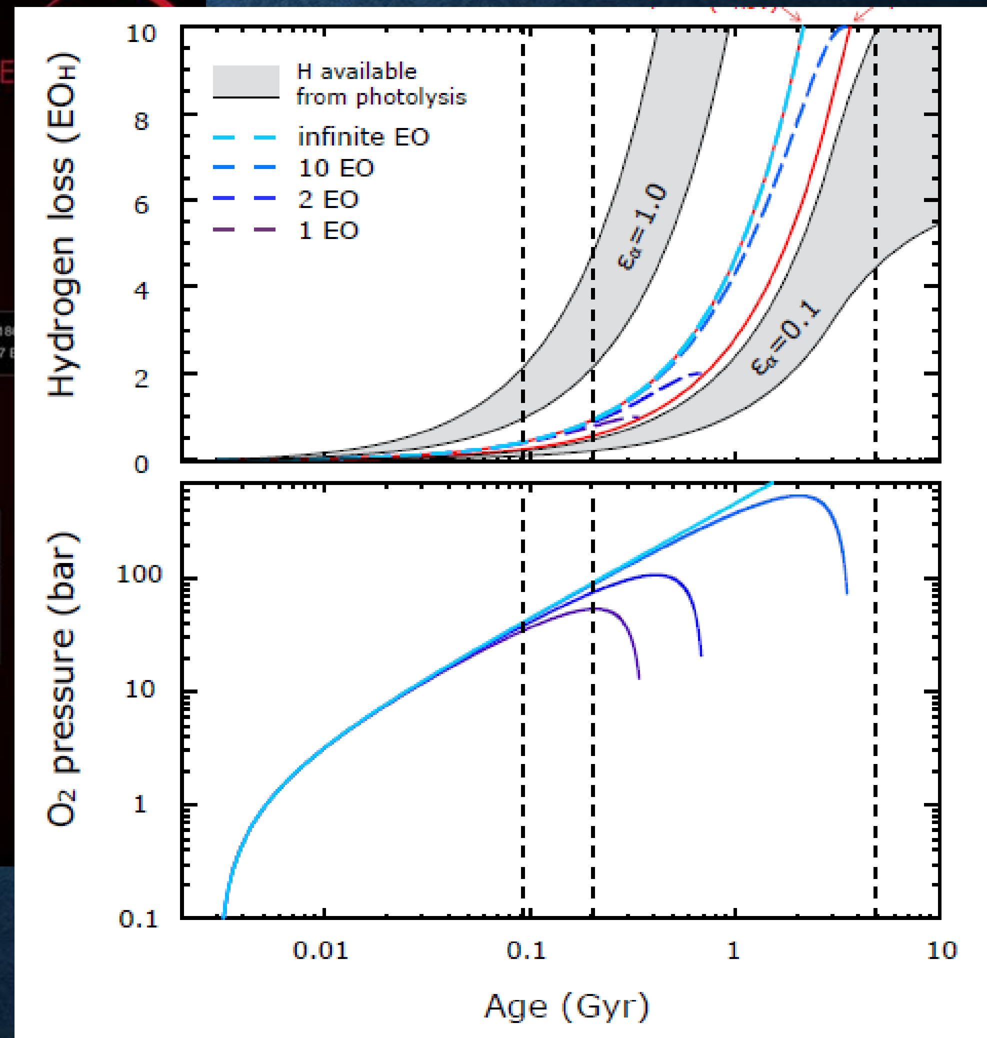
M dwarf EUV: Allison Youngblood - CU

Example: Water on Proxima Cen b



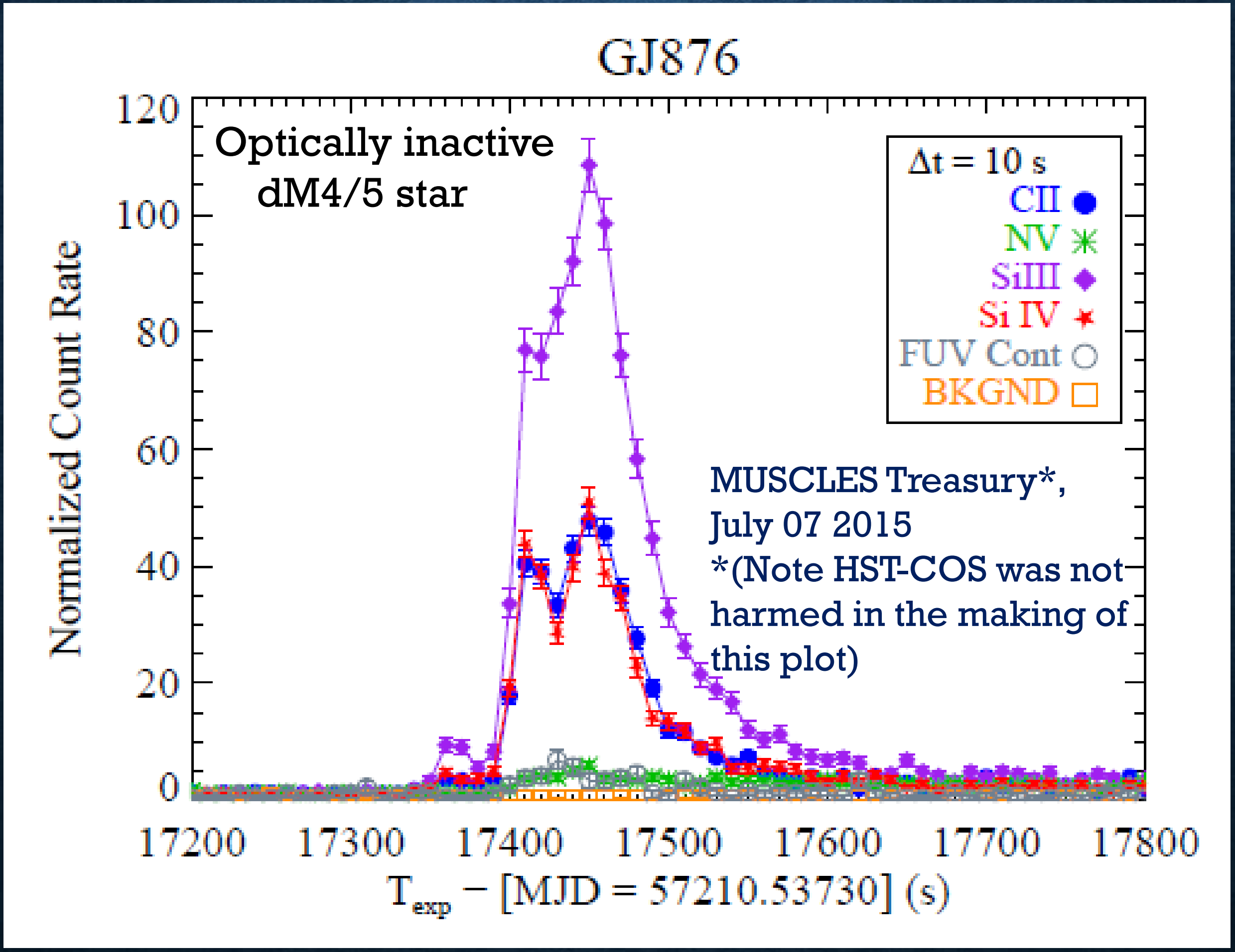


ProxCen b:(Anglada-Escude et al. 2016)



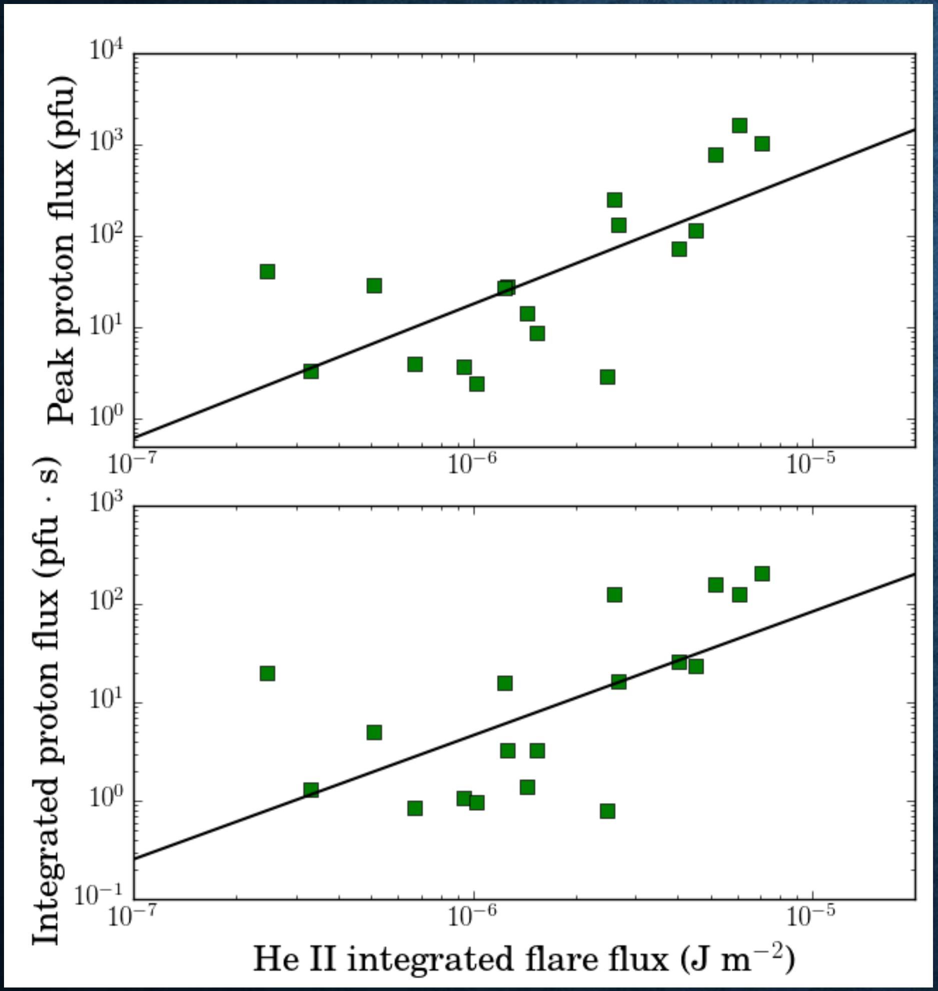
(Ribas et al. 2016)

Question B: How do impulsive events (flares and energetic proton events) impact the composition of a planet's atmosphere?



France et al. (ApJ-2016)

Estimating proton fluxes from UV flare data



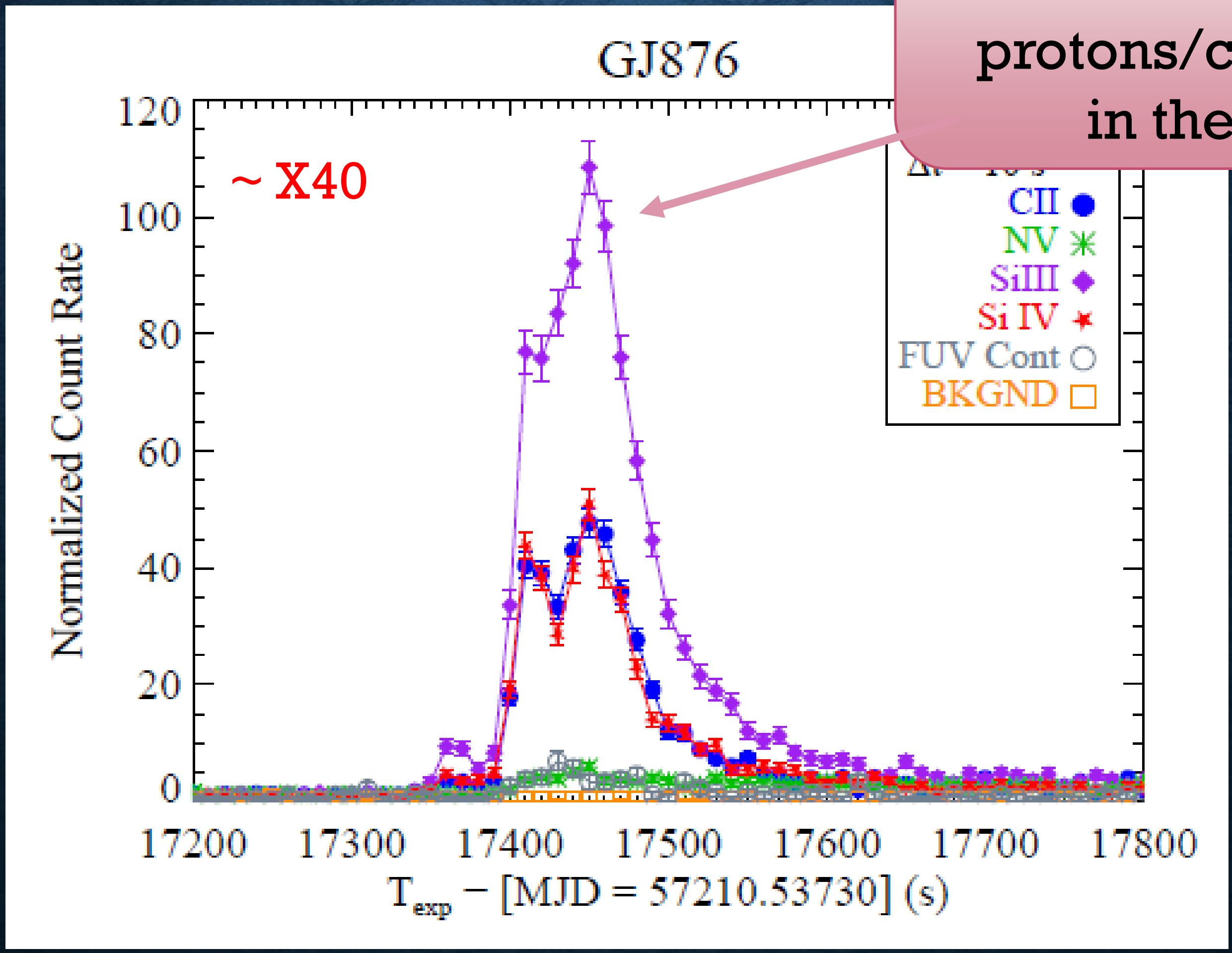
- **Combining solar flare and CME catalogs from GOES and SDO-EVE over a 4 year period, we developed flare-to-CME relationships**
- **He II has comparable formation temperature to many FUV lines in the MUSCLES sample**

(w/Fontenla et al. 2016 semi-empirical M dwarf atmosphere models)

Youngblood, France et al. (ApJ - 2017)

IMPULSIVE EVENTS: FLARES AND ENERGETIC PARTICLE EVENTS

- FUV Flare on GJ 876.



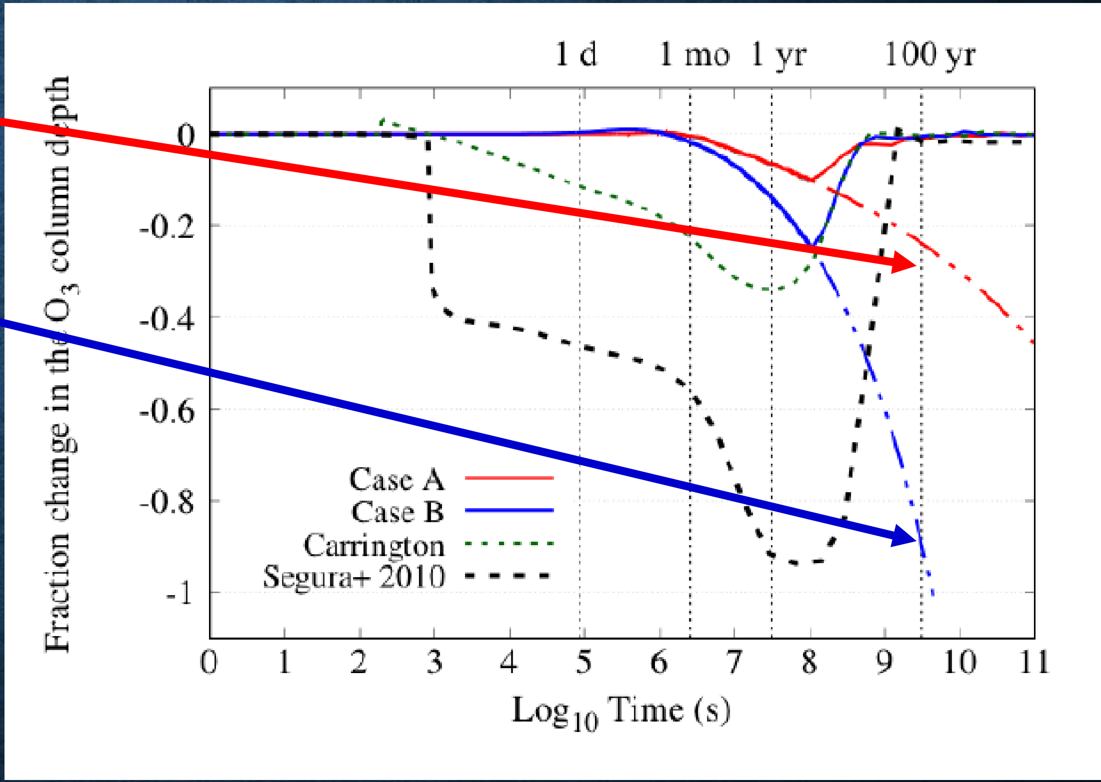
~2500
> 10 MeV
protons/cm^2/s/sr
in the HZ

France et al. (ApJ-2016)
Loyd et al. (ApJ-2017 in prep)

IMPULSIVE EVENTS: FLARES AND ENERGETIC PARTICLE EVENTS

Atmospheric Erosion:

- **Conservative flare rate ($T_{dep}(O_3)$ = 318 kyr)**
- **GJ 876 flare rate ($T_{dep}(O_3)$ = 160 yr)**



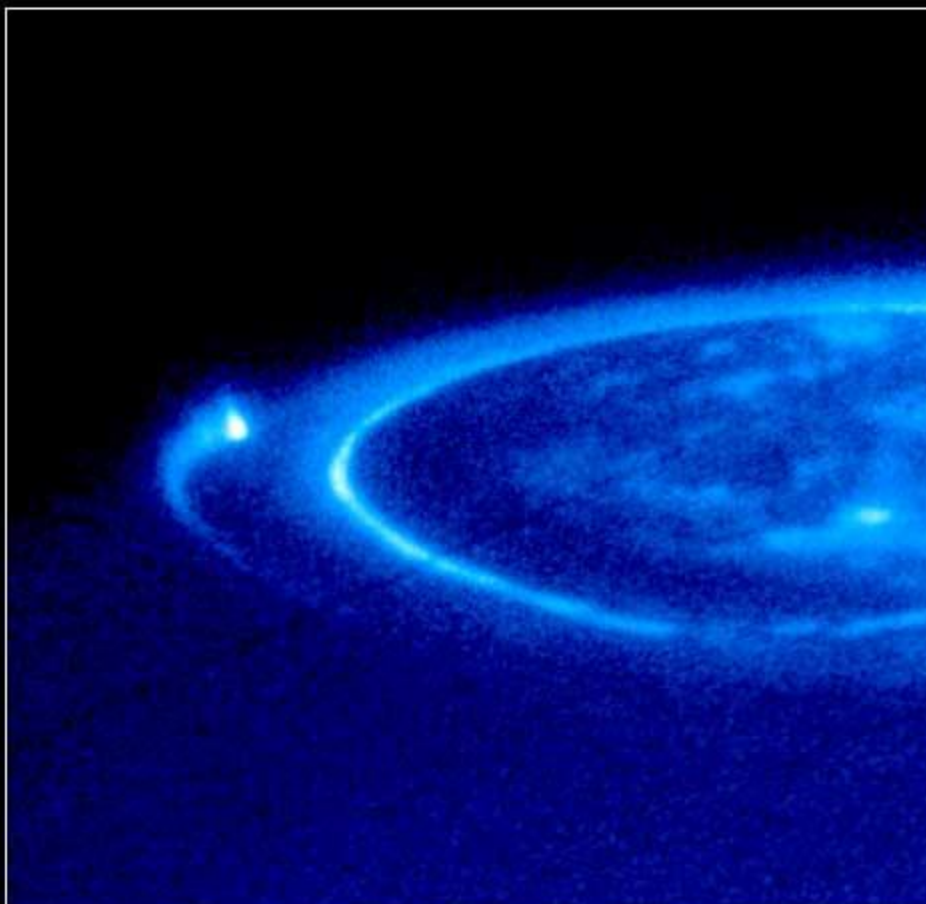
- **JWST or TMT observations may find a lack of ozone: lack of life or stellar influence?**

see also Airapetian et al. (2016): strong flares generating greenhouse gases and prebiotic chemistry on early Earth

Youngblood, France et al. (ApJ - 2017)

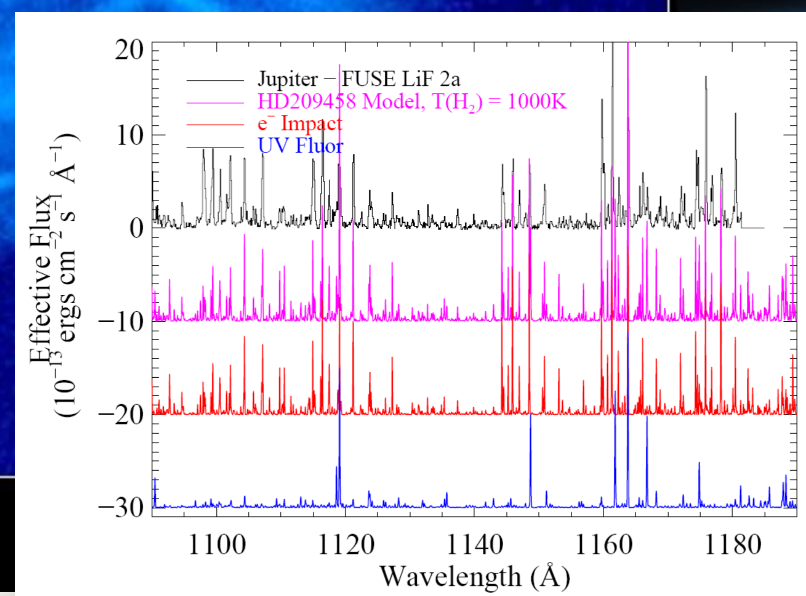
UV emission from exo-aurorae

UV emission from exo-aurorae



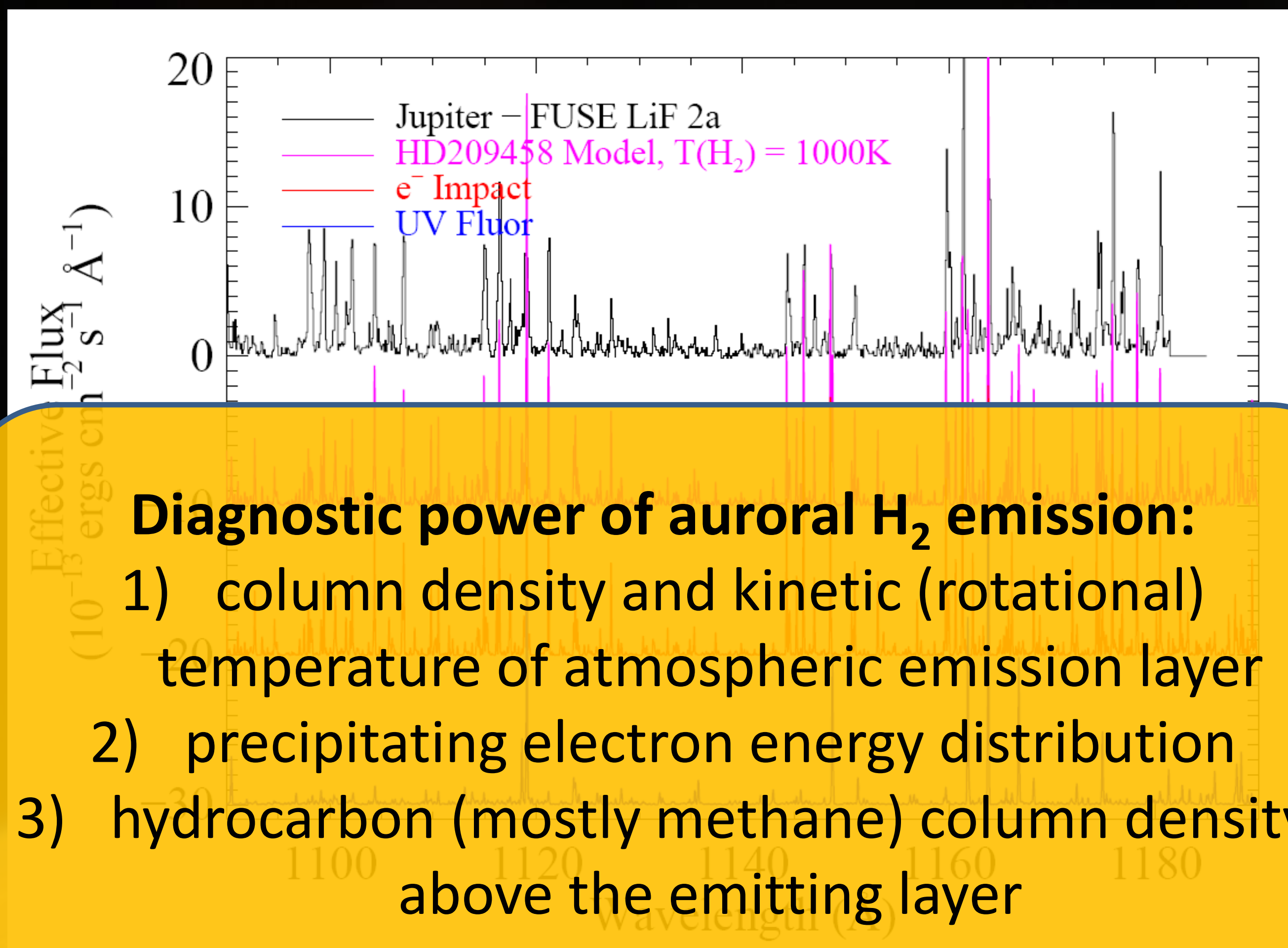
Jupiter Aurora

NASA and J. Clarke (University of Michigan) • STScI-PRC00-38



Gustin et al. (2004)
Icarus, 171, 336

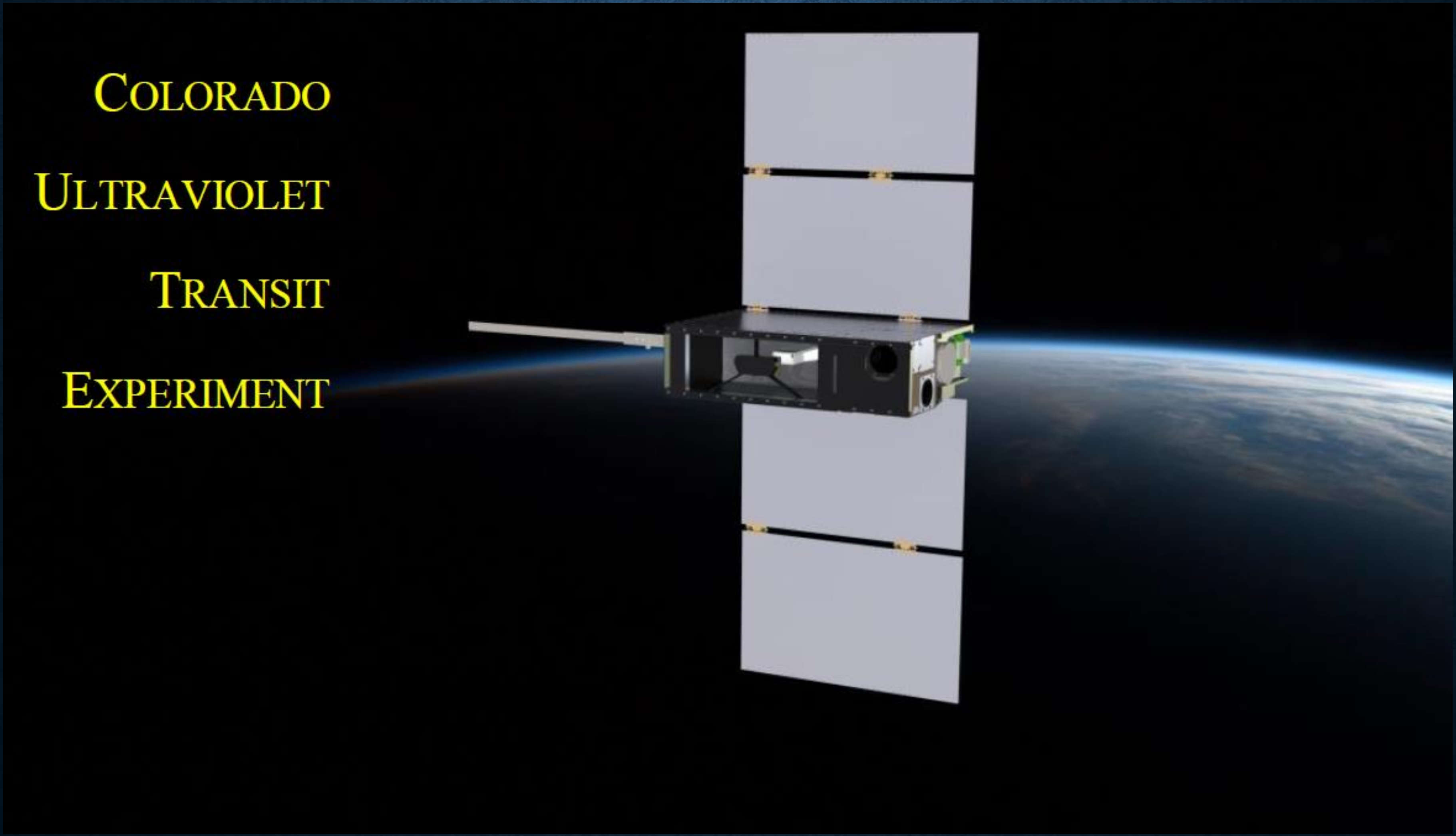
UV emission from aurorae/dayglow



Diagnostic power of auroral H_2 emission:

1) column density and kinetic (rotational) temperature of atmospheric emission layer
2) precipitating electron energy distribution
3) hydrocarbon (mostly methane) column density above the emitting layer

DEDICATED SMALL SPACE INSTRUMENS



DEDICATED SMALL SPACE INSTRUMENS

COLORADO

ULTRAVIOLET

TRANSIT

EXPERIMENT

Survey of ~15 short-period transiting planets around nearby stars:

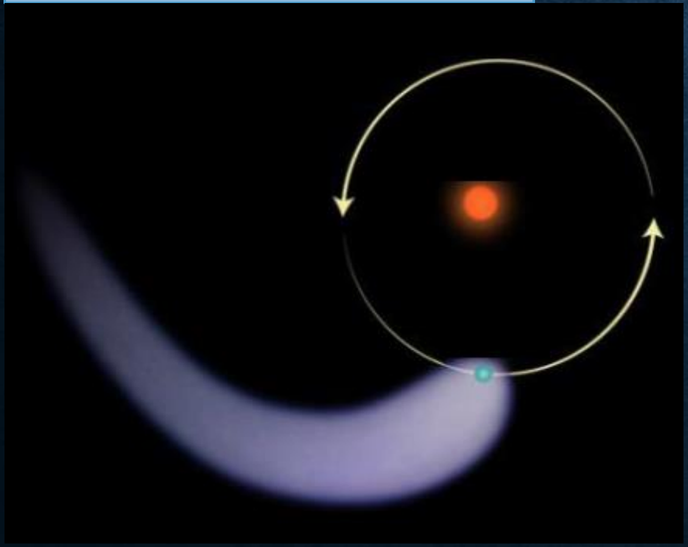
1) Atmospheric mass-loss
2) Exoplanet Magnetic Fields?

<u>CUTE Scientists</u> (??)
PI – K. France
PS – B. Fleming
PE – R. Kohnert
(U Colorado)

<u>External Science Team</u>:
L. Fossati (U Graz)
A. Vidotto (Trinity/Dublin)
T. Koskinen (U of A/LPL)
J-M. Desert (U Amsterdam)
P. Petit (IRAP/Toulouse)

DEDICATED SMALL SPACE INSTRUMENS

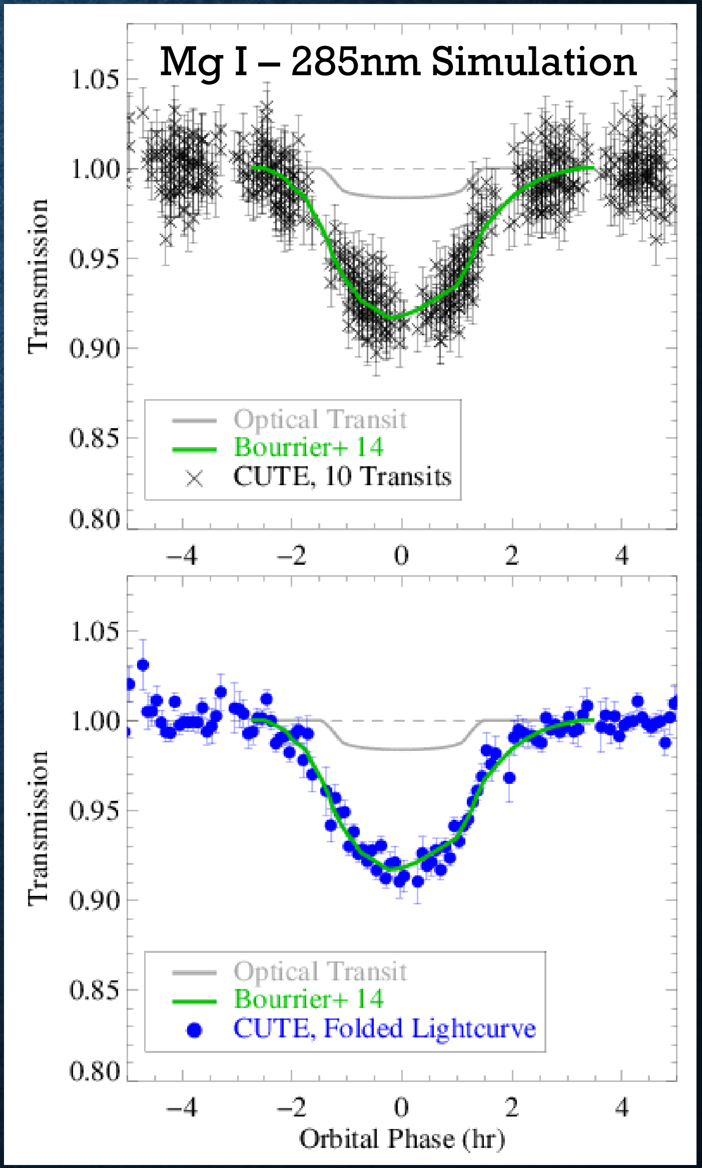
Colorado
Ultraviolet
Transit
Experiment



Survey of ~15 short-period transiting planets around nearby stars:

1) Atmospheric mass-loss & Variability

NUV Transit Spectro-photometry

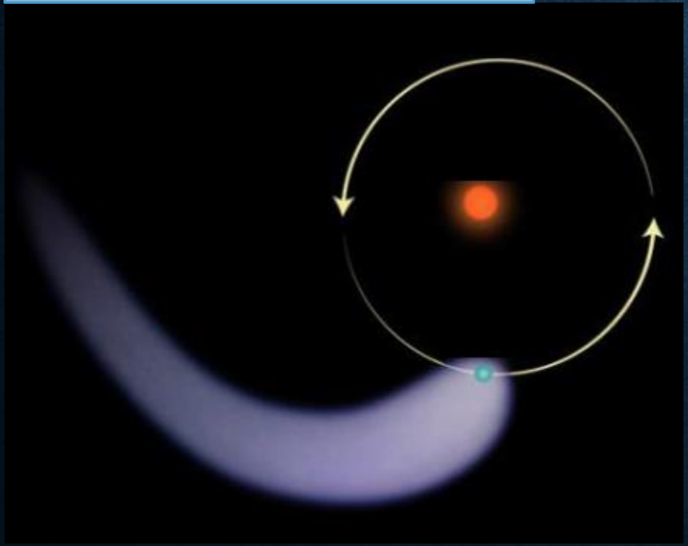


DEDICATED SMALL SPACE INSTRUMENS

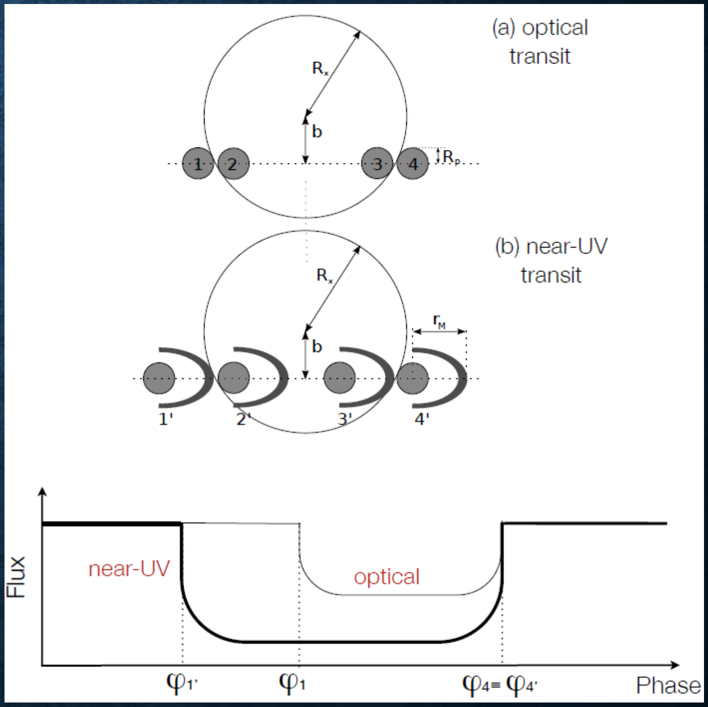
Colorado
Ultraviolet
Transit
Experiment

Survey of ~15 short-period transiting planets around nearby stars:

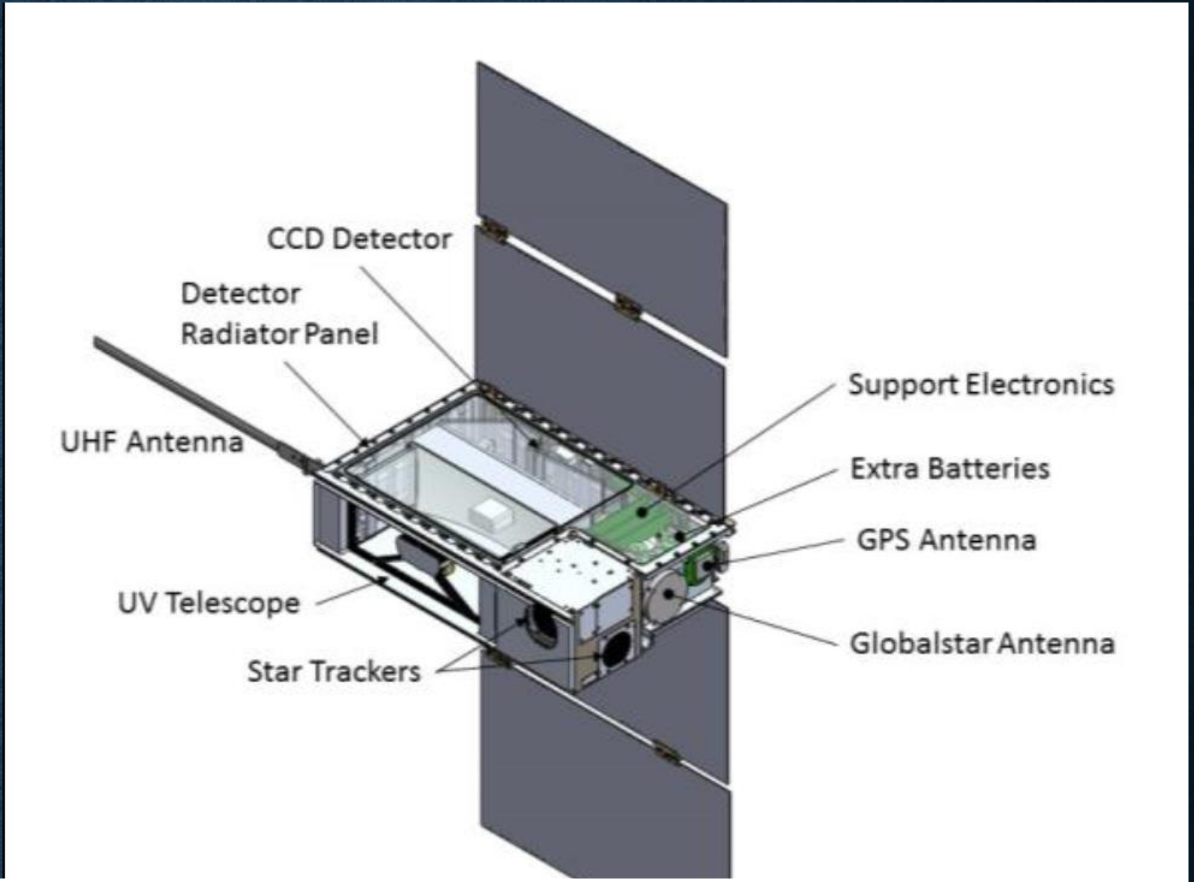
1) Atmospheric mass-loss
2) Exoplanet Magnetic Fields?

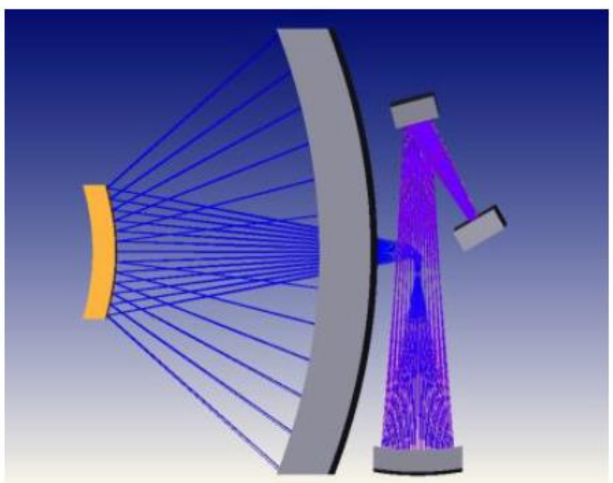


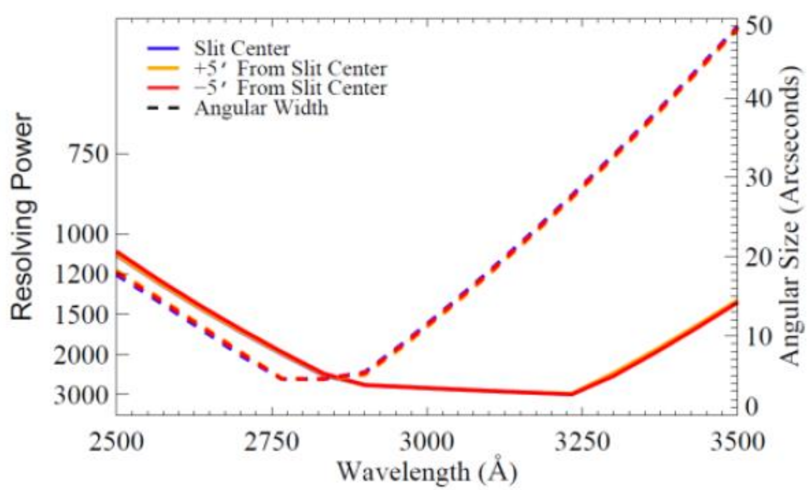
Light curve asymmetry to distinguish between magnetic and mass-loss supported bow shocks



Colorado
Ultraviolet
Transit
Experiment



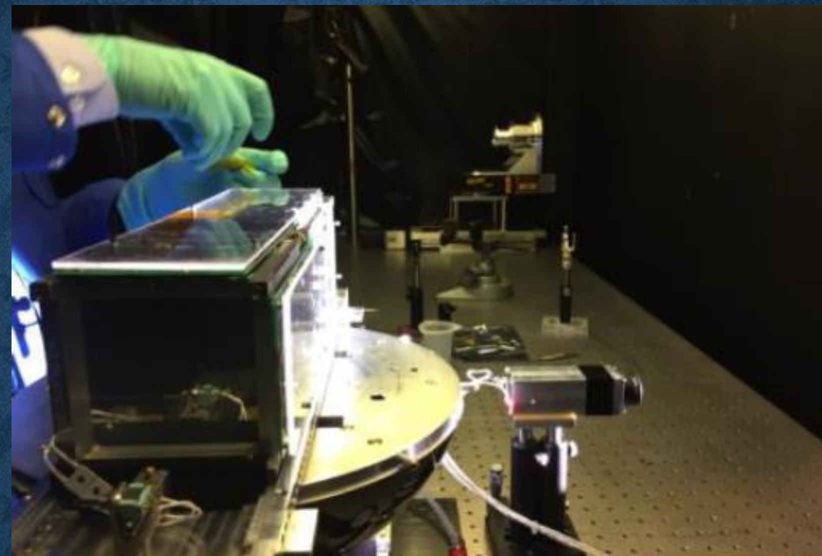


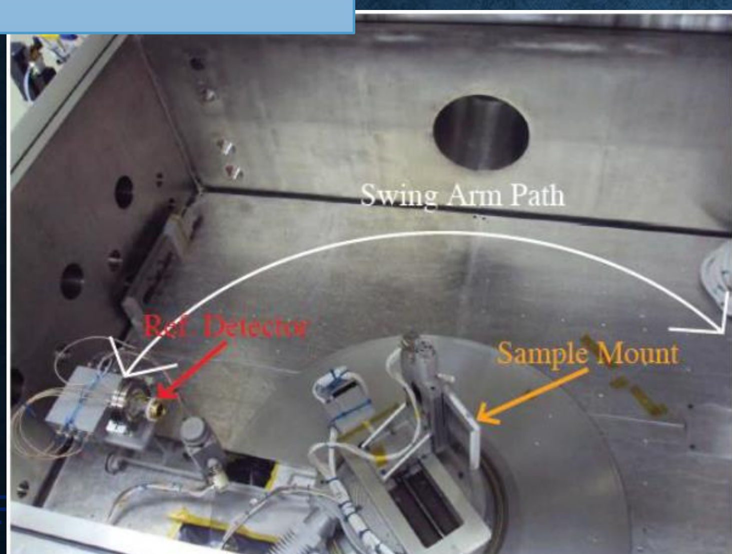


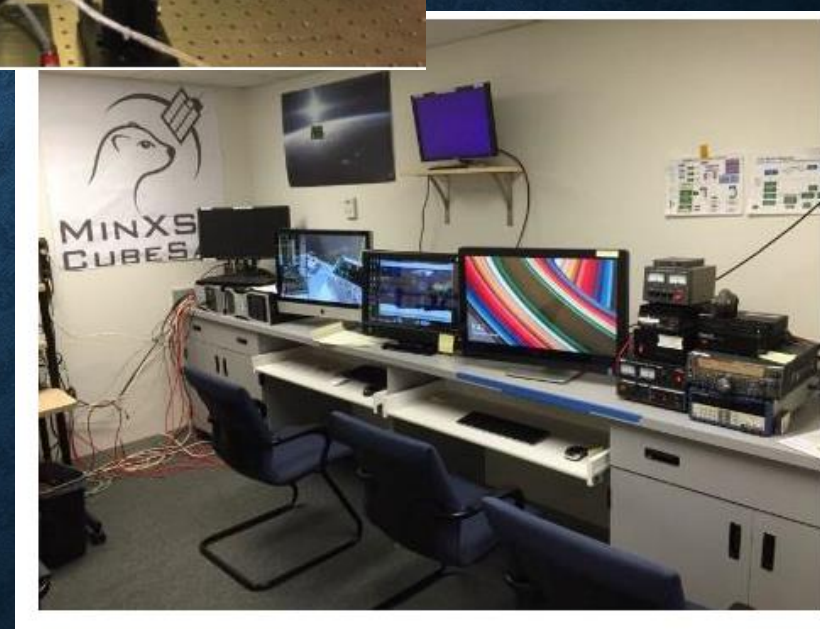
PI –

DEDICATED SMALL SPACE INSTRUMENS

Colorado
Ultraviolet
Transit
Experiment







PI – F

Ultraviolet Observations of Star-planet Interactions – Current Status and Future Directions

- Kevin France, University of Colorado

1) High EUV irradiance can drive high mass-loss rates. Metals can be "dragged" along by high H and He outflow rates. 5 – 50% transit depths and large asymmetries can result. **[FUV chromospheric lines]**

2) Magnetically supported bow-shock, hydrodynamic mass-loss, and/or accretion of atmospheric material can cause early ingress asymmetries **[NUV absorption lines]**

3) Enhanced magnetospheric activity observed with orbital phase or the proximity of massive planet **[FUV transition region lines]**

4) F**uture:** Larger samples of FUV emission line measurements, coordinating UV stellar observations with vis/IR planetary spectroscopy, exoplanetary aurorae, and spectroscopic monitoring of short-period transiting planets


END