The upper atmospheres of the ice giants

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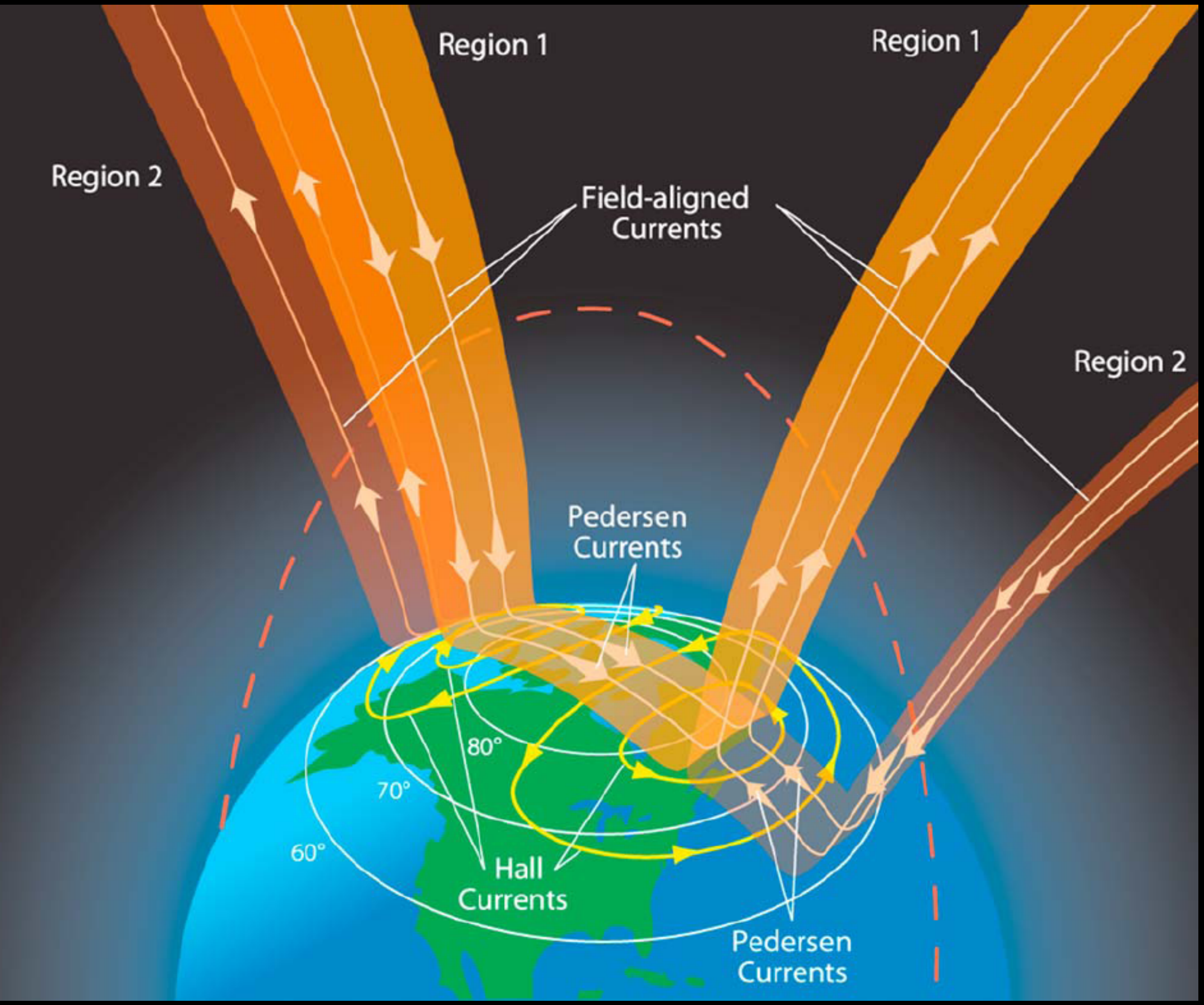
Upper atmosphere - definition

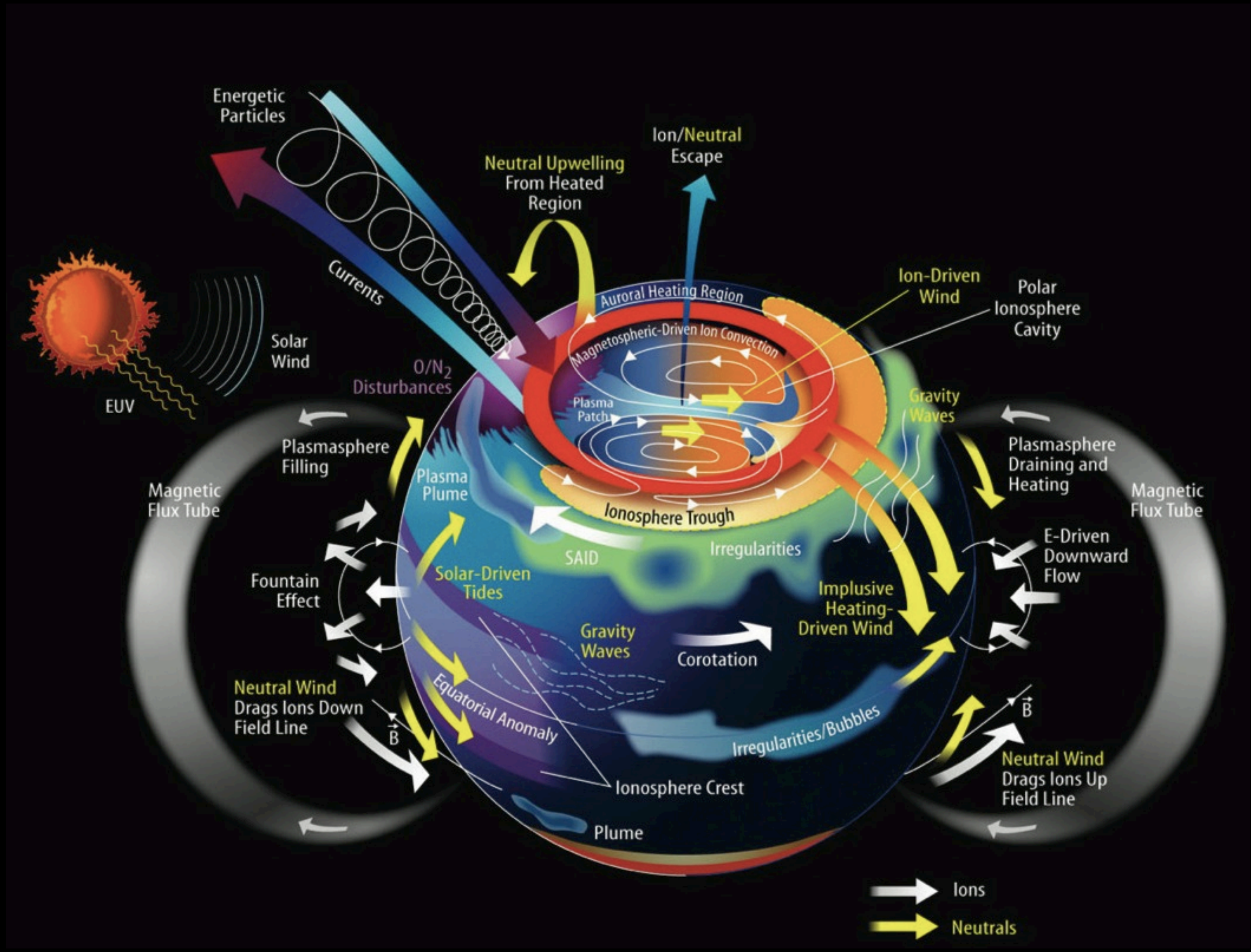
- Situated above the homopause - above which molecular diffusion dominates over eddy diffusion (turbulent mixing)
- Each species is distributed according to its own scale height, dependent on mass. Dominated by light species.
- Low density
- Two basic components: neutral thermosphere and charged particle ionosphere
- The molecular ion H_3^+ is a dominant ion in the ionosphere and is observable using ground-based telescopes

Why do we care?

The ionosphere feels the magnetic field and the processes within it

The upper atmosphere connects the planet to the surrounding space environment



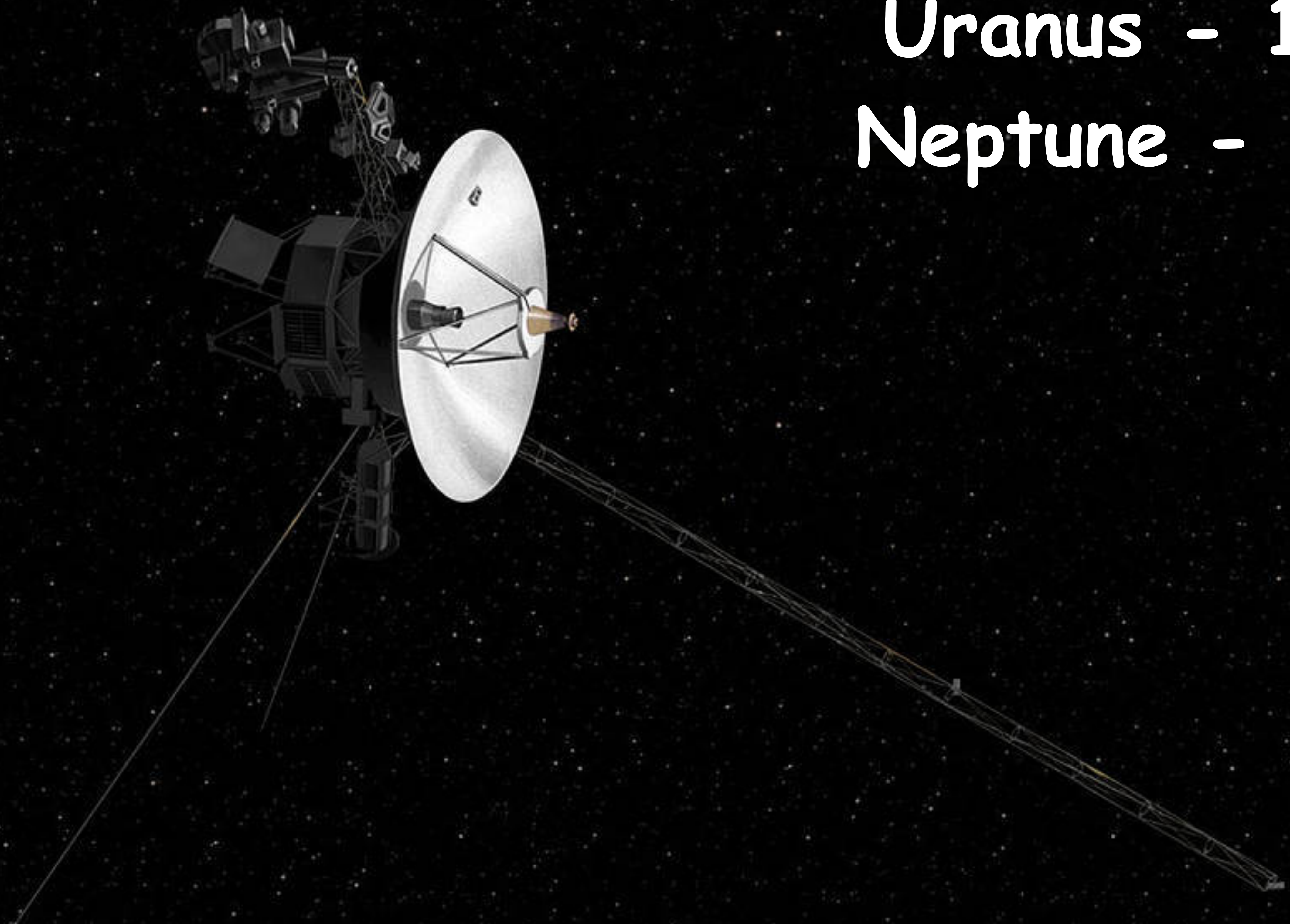


NASA

Voyager 2

Uranus - 1986

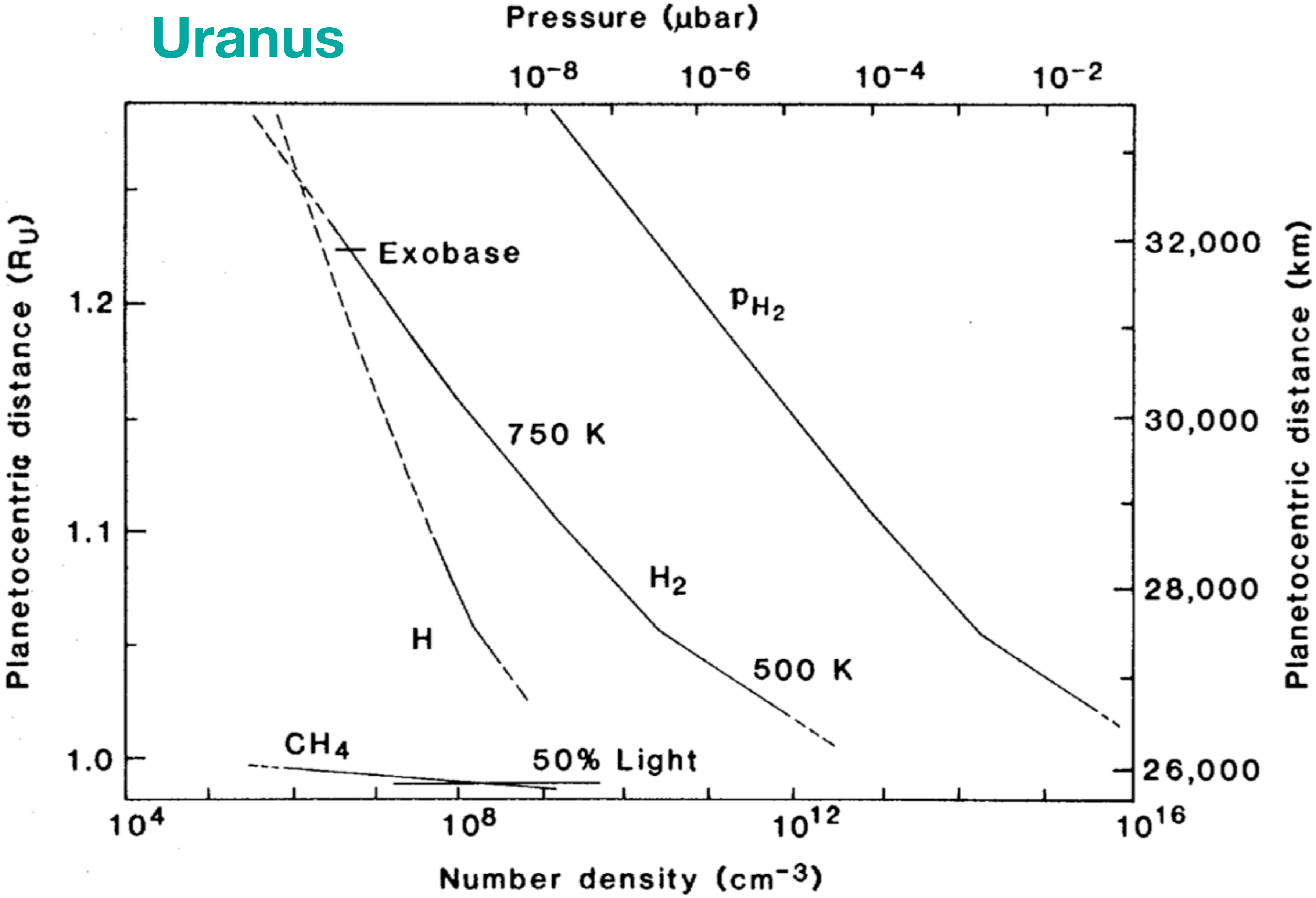
Neptune - 1989



Atmospheric structure

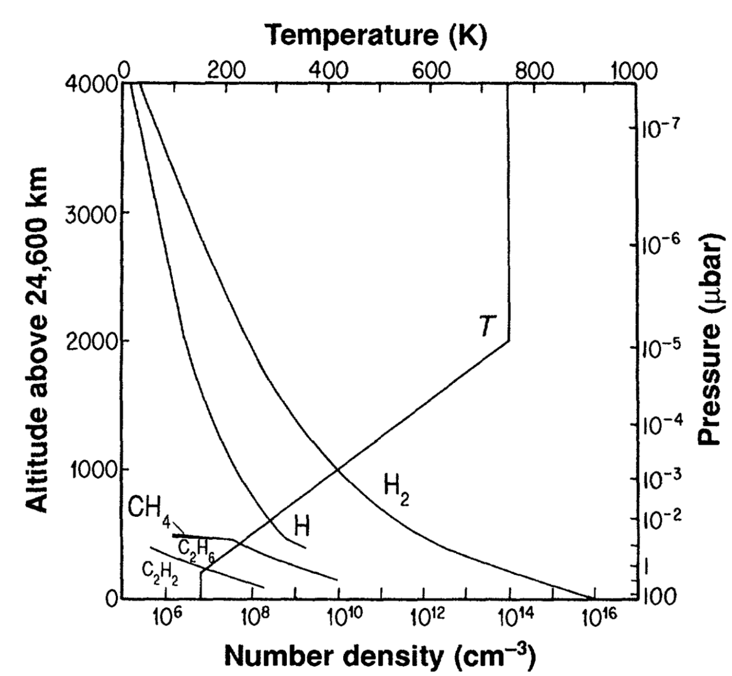
Derived from ultraviolet solar occultations of the upper atmosphere using the Voyager 2 Ultraviolet Spectrometer (UVS)

Uranus



Broadfoot et al. (1986)

Neptune



Broadfoot et al. (1989)

Energy Crisis!

The predicted temperature based on solar input alone is several hundreds of Kelvins less than is observed!

335

Comparison of predicted and measured exospheric temperatures.

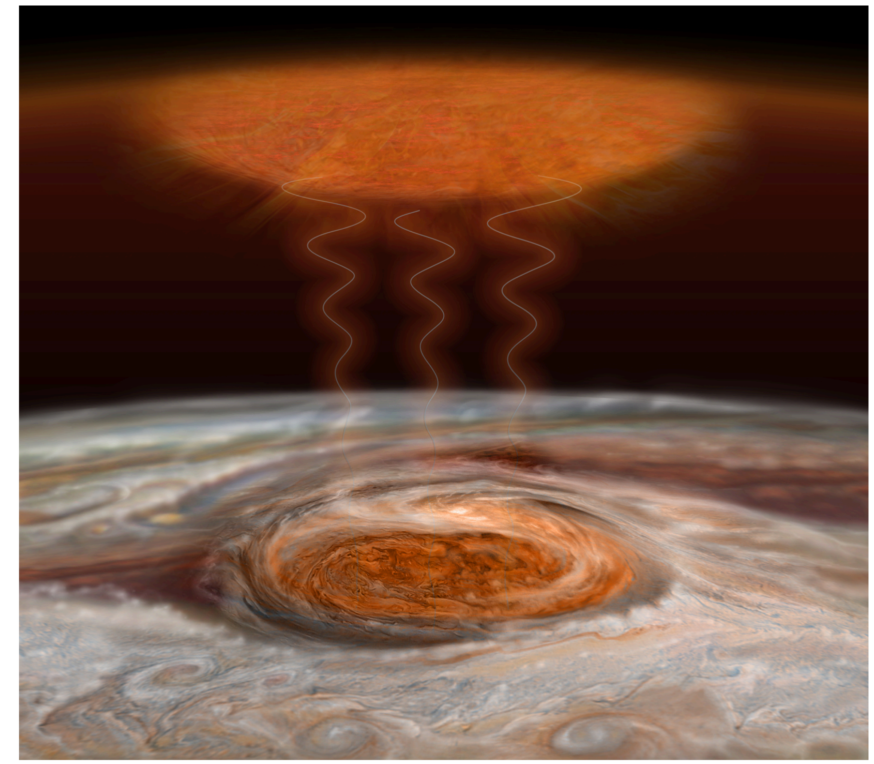
	Jupiter	Saturn	Uranus	Neptune
Heliocentric distance (AU)	5.20	9.57	19.19	30.07
Absorbed solar flux (W m^{-2})	3.7×10^{-5}	1.1×10^{-5}	2.7×10^{-6}	1.1×10^{-6}
T_{exo} (observed) [K]	940	420	800	600
T_{exo} (calculated) [K]	203	177	138	132
ΔT_{exo} (obs-calc) [K]	737	243	662	468

Yelle & Miller (2004)

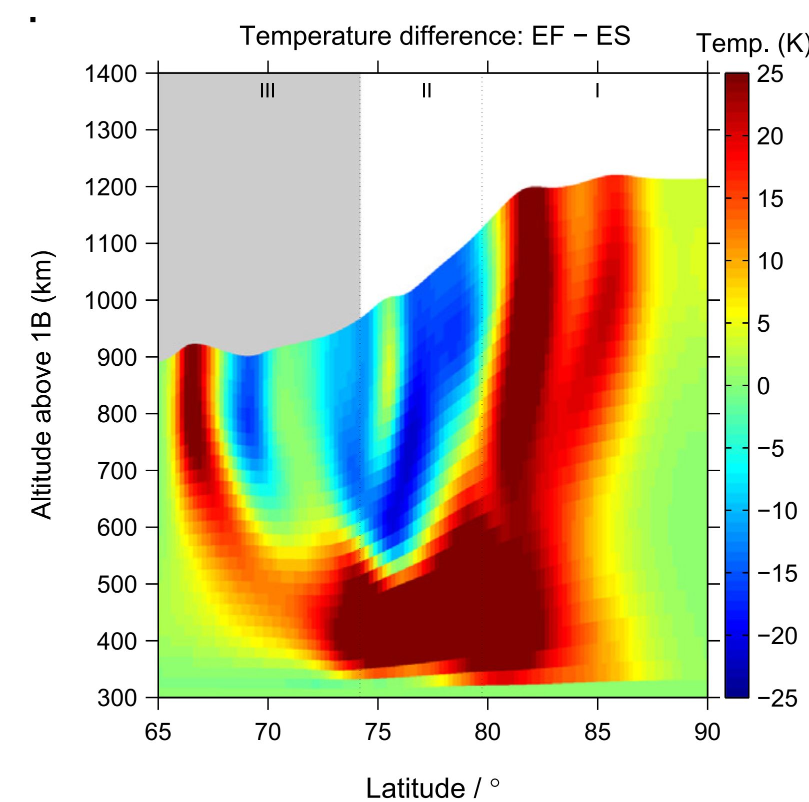
Observed temperature minus predicted temperature

Ways to heat a thermosphere

- ~~Heating by solar EUV radiation.~~
- Heating from lower altitudes via the breaking of gravity waves (e.g. O'Donoghue et al., 2016 for Jupiter)
- Heating injected by the magnetsphere/ionosphere/ thermosphere interaction - Joule heating combined with global re-distribution of this energy (e.g. Yates et al., 2015 for Jupiter).
- Other?



O'Donoghue et al., (2016)

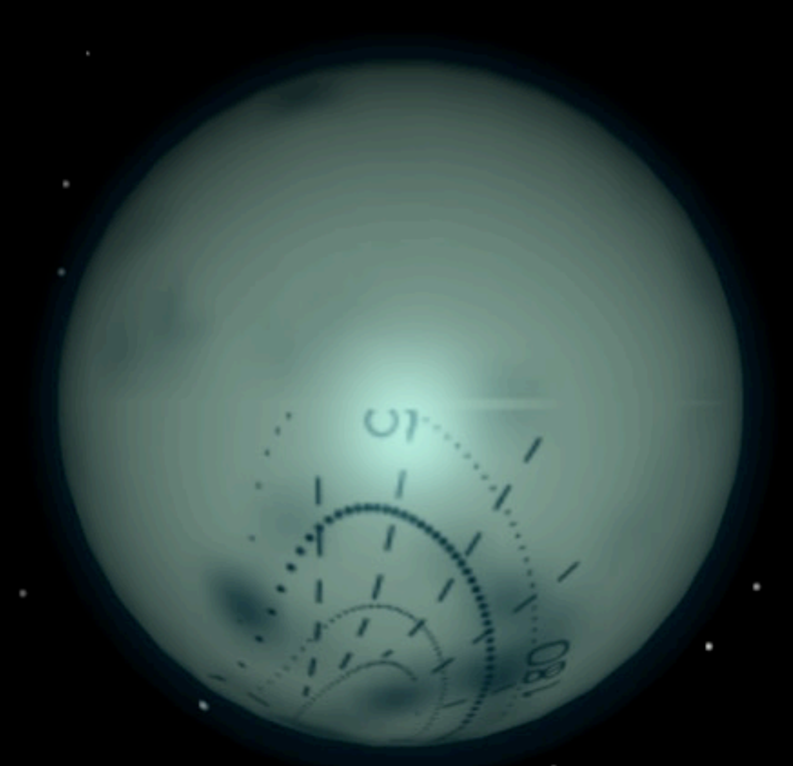


Yates et al., (2014)

Ice giant auroral emissions

Uranus

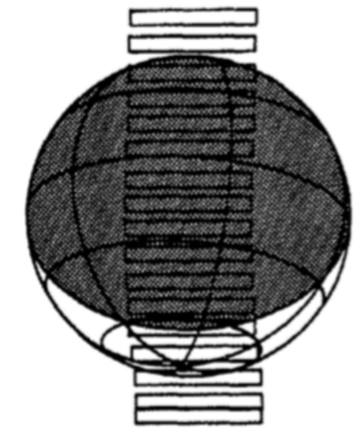
Auroral H_2 emission mapped to equinoctial geometry

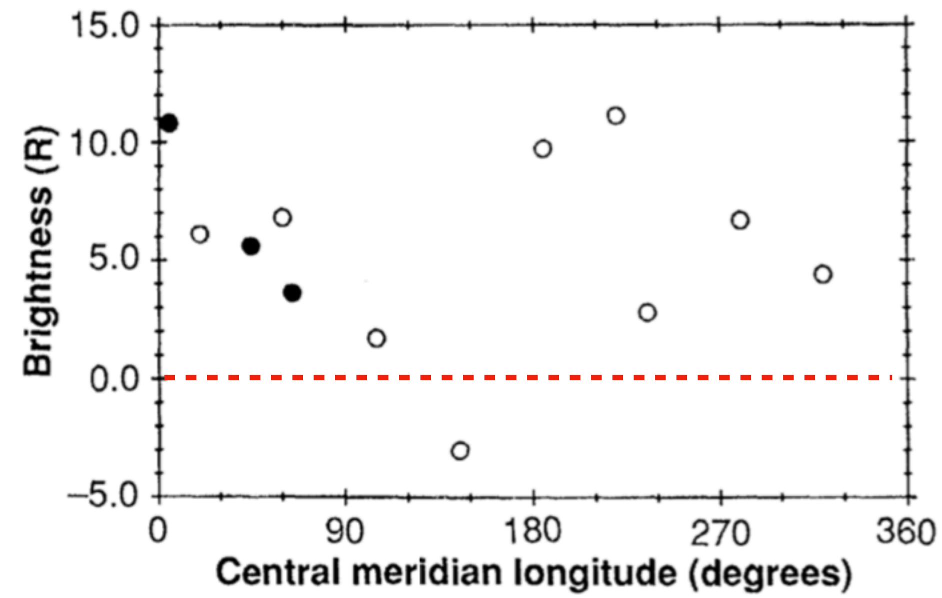


Voyager 2 - Herbert (2009)

Hubble Space Telescope
Lamy et al. (2012, 2017, 2018)
Later this afternoon!

Neptune





Brightness of H_2 emission observed in the far-ultraviolet
Broadfoot et al. (1989)

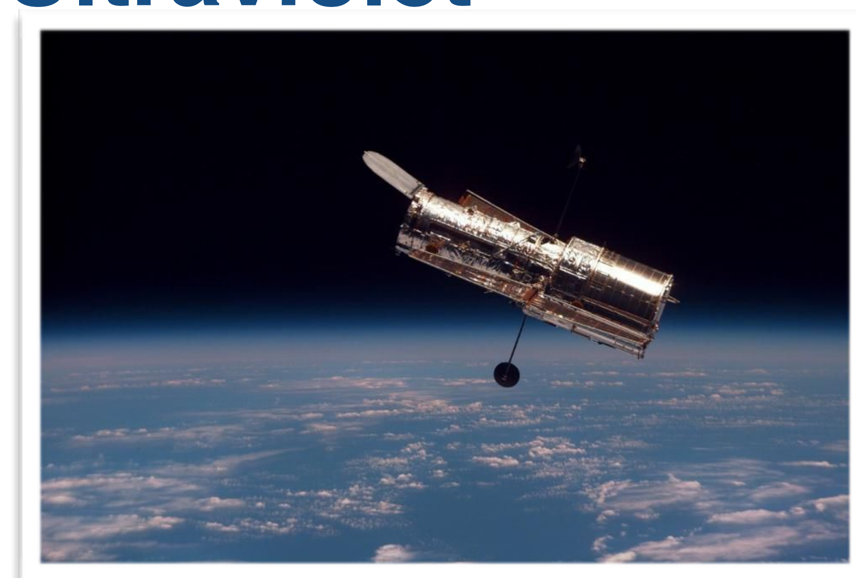
Some Very Simple Chemistry (in the Upper Atmosphere)

Energy — Solar photons, Energetic particles

$\downarrow$

H & H_2

Excitation $\rightarrow$ **Ultraviolet**



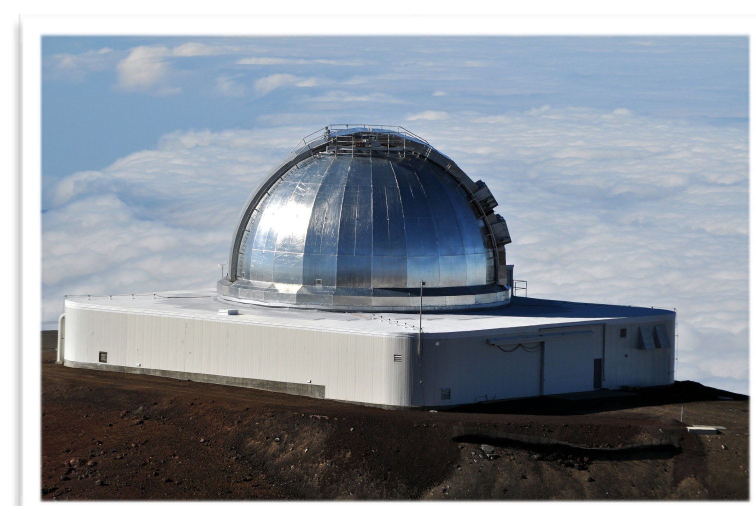
Ionization $\downarrow$

H_2^+

$H_2 \rightarrow H_2^+ \rightarrow H_3^+$

$H_2 \rightarrow$ **Infrared**

$H_3^+ \rightarrow$ **Infrared**



The molecular ion H_3^+

$$\mathrm{H_2^+} + \mathrm{H_2} \longrightarrow \mathrm{H_3^+} + \mathrm{H}$$

Intensity $I = N \dfrac{K^i}{Q(T)} \exp\left(-\dfrac{hc\omega_u^i}{kT}\right),$

Number density

Temperature

Loss mechanisms

$$\mathrm{H_3^+} + \mathrm{e^-} \longrightarrow \mathrm{H_2} + \mathrm{H}$$

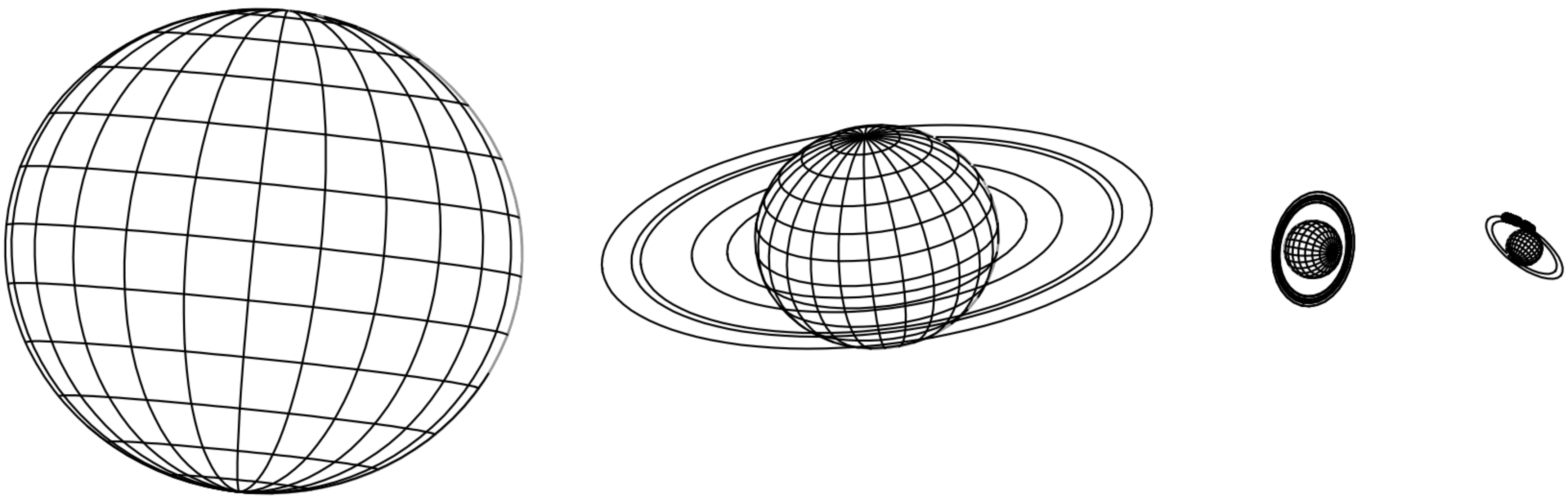
$$\mathrm{H_3^+} + \mathrm{e^-} \longrightarrow \mathrm{H} + \mathrm{H} + \mathrm{H}$$

$$\mathrm{H_3^+} + \mathrm{X} \longrightarrow \mathrm{HX^+} + \mathrm{H_2}$$

H_3^+ cannot coexist with CH_4

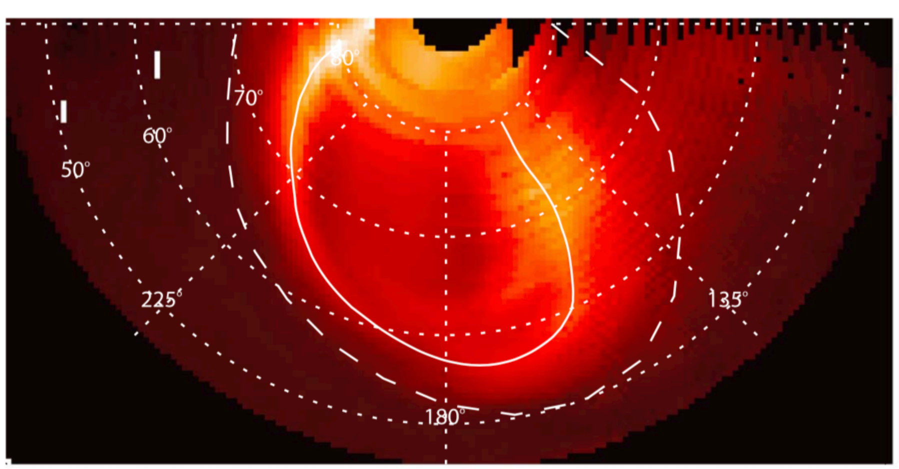
H_3^+ as seen from the Earth

Apparent relative sizes at this moment (2020-01-20)



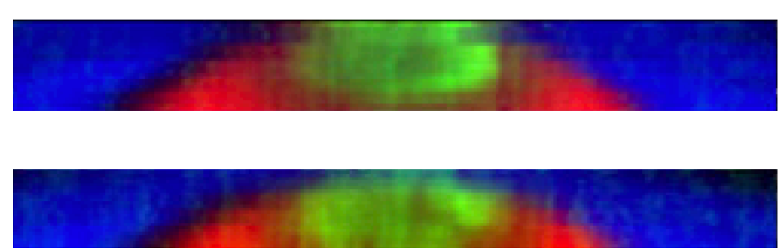
Jupiter **Saturn** **Uranus** **Neptune**

VLT CRIRES



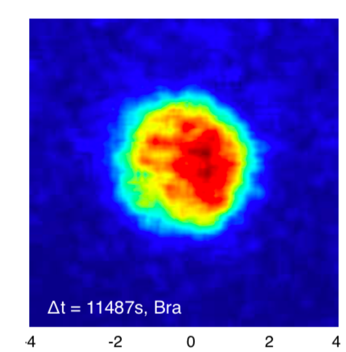
Johnson et al. (2018)

Keck NIRSPEC



Stallard et al. (2019)

Gemini NIRI



Lamy et al. (2018)

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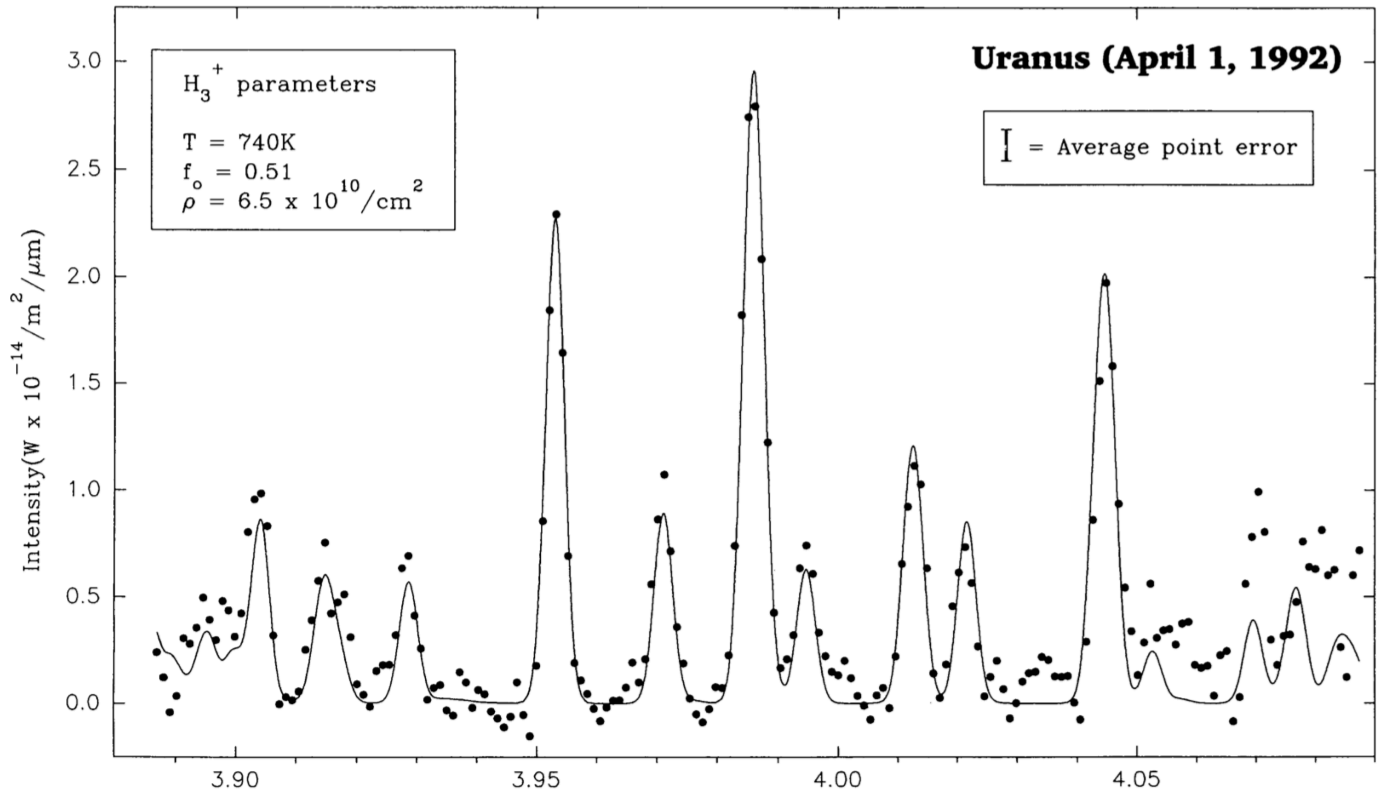
Detection of H_3^+ at Uranus

United Kingdom Infrared Telescope



Trafton et al. (1993) discovered H_3^+ at Uranus
Disk averaged temperature of 740 K

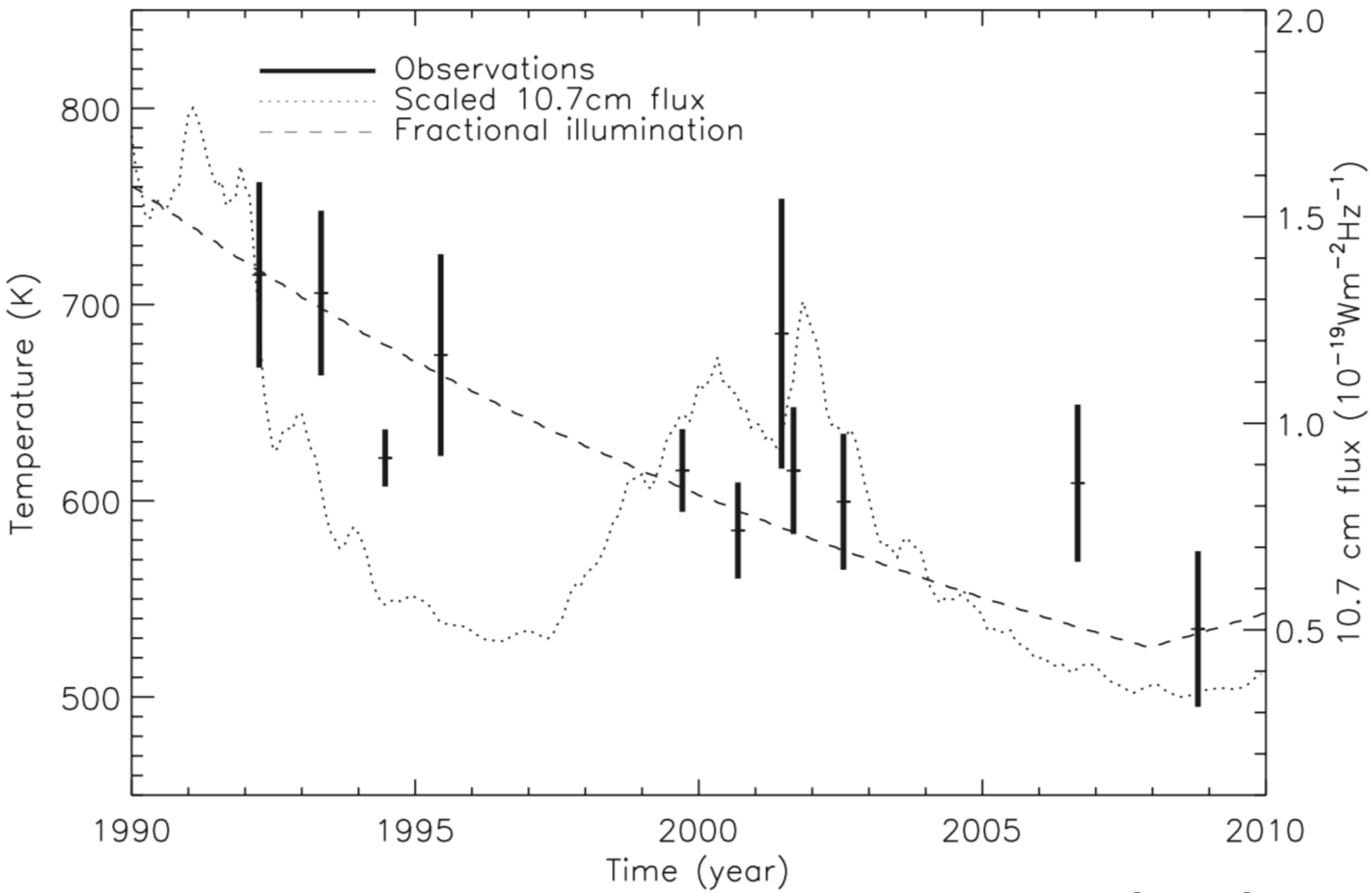
Similar to the 750 K derived by Voyager 2

Intermittent observations between 1992 and 2009:
e.g. Lam et al. (1997), Trafton et al. (1999), Encrenaz et al. (2003)

Initial study

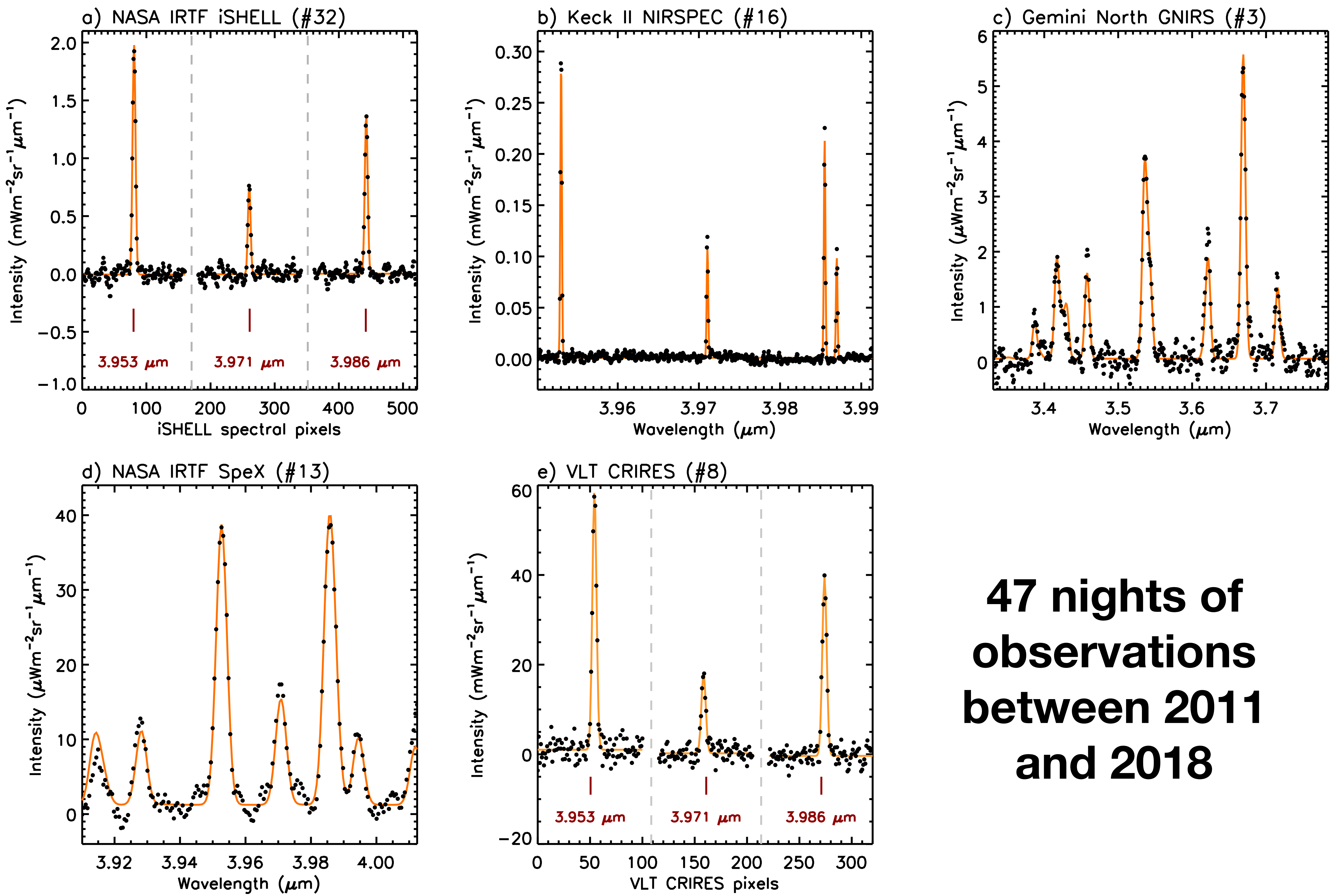
Re-analysed all available observations of H_3^+ from Uranus

Globally averaged temperature of the upper atmosphere as a function of time



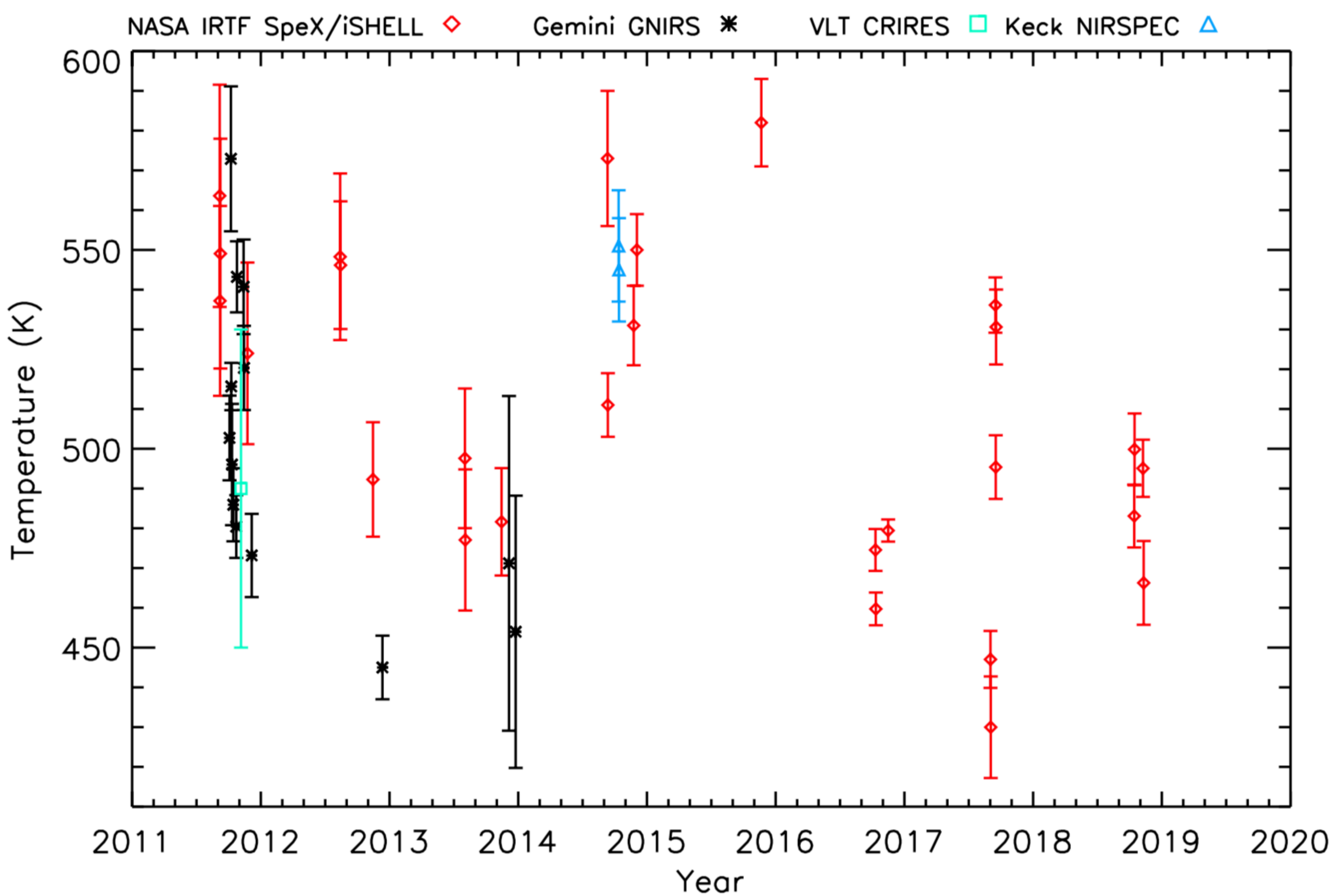
Melin et al., (2011)

New observations of H_3^+ form Uranus



47 nights of observations between 2011 and 2018

New observations

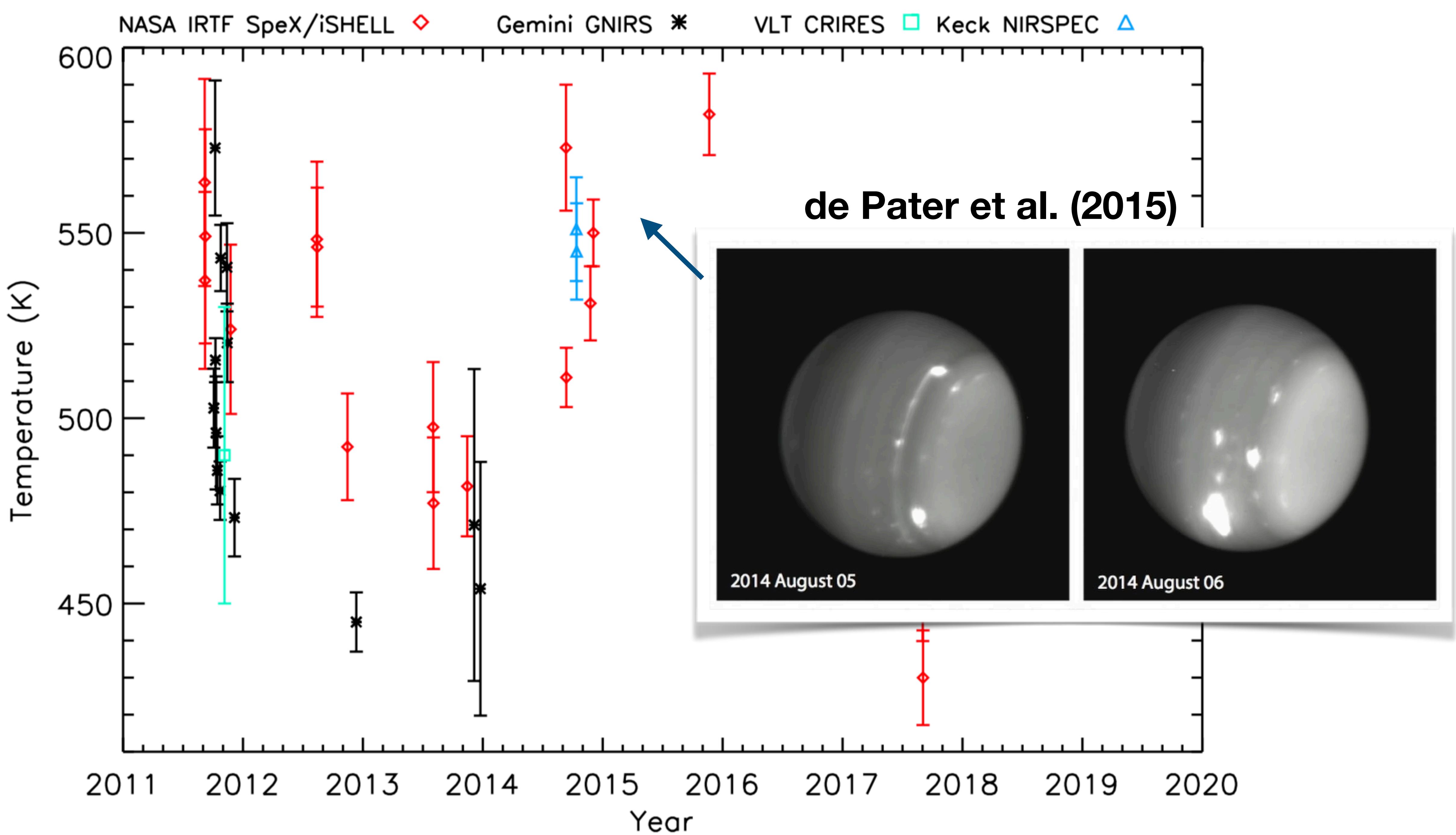


Lots of scatter

2014 & 2015 stands out as hotter than the rest

Calculate yearly averages

New observations



Lots of scatter

2014 & 2015 stands out as hotter than the rest

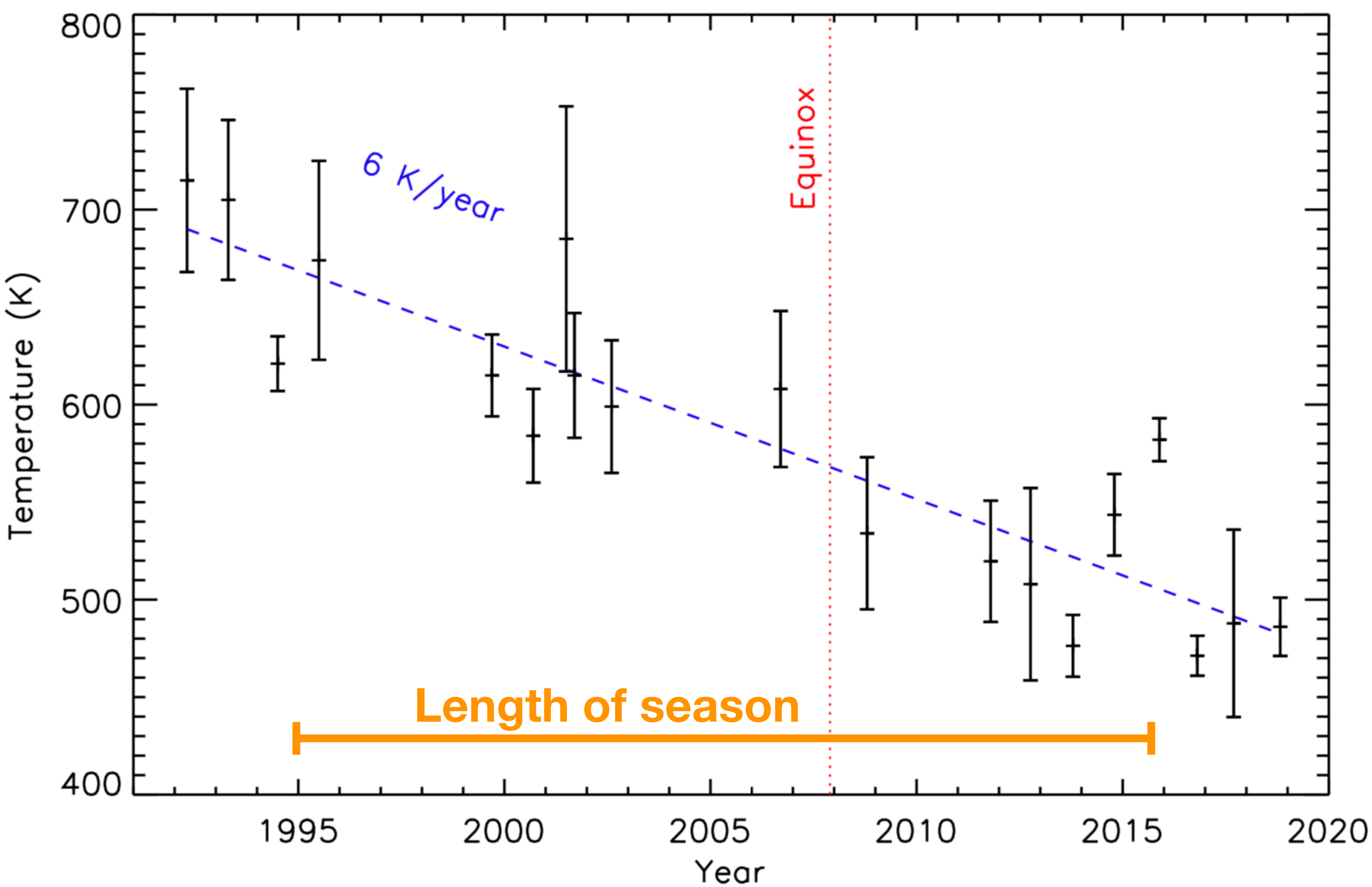
Calculate yearly averages

Long-term variability

One of a kind long-term dataset

Continuous cooling for 27 years - longer than length of season!

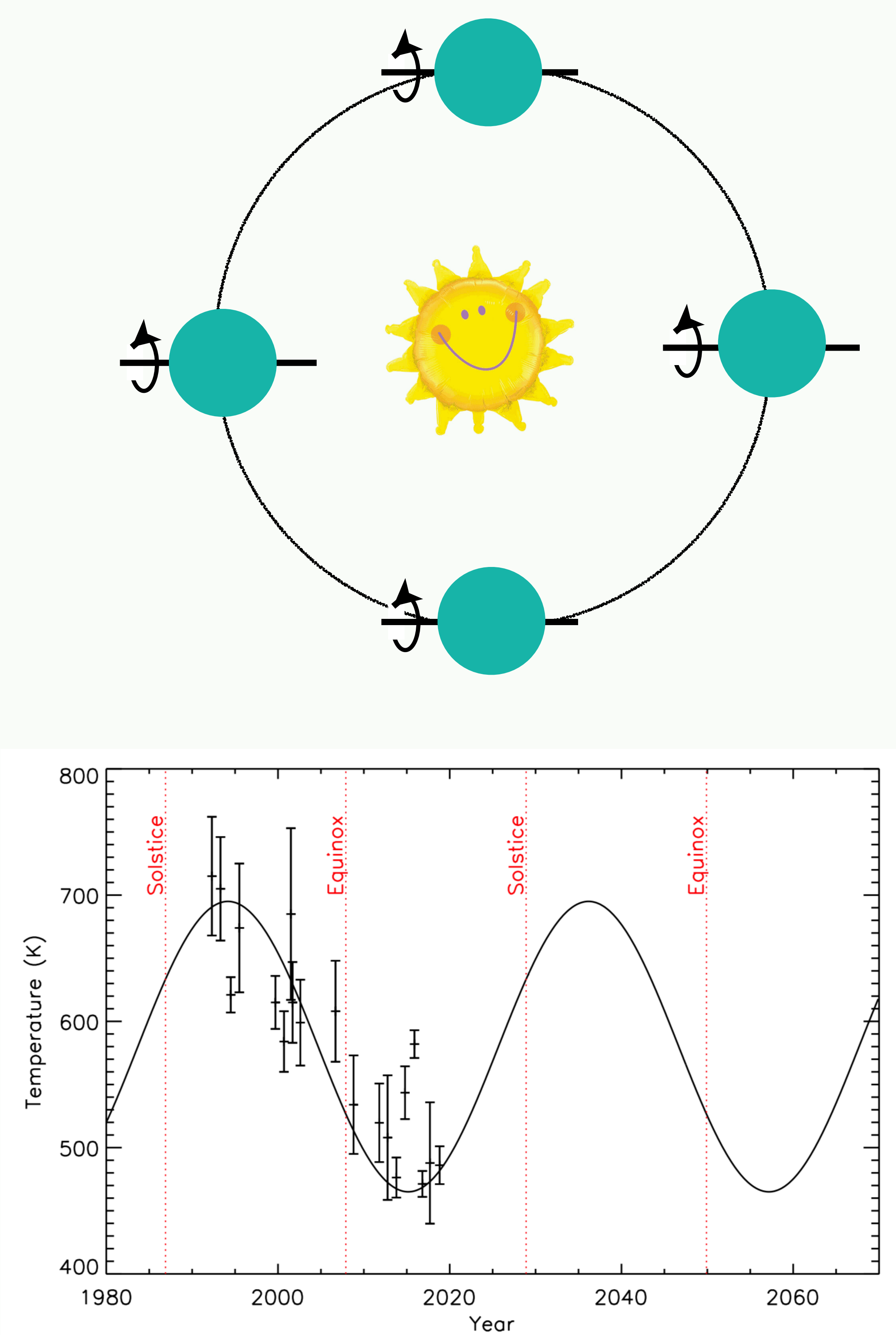
Cooling means less intense H_3^+, 2018 intensity is ~5% of 1992 intensity

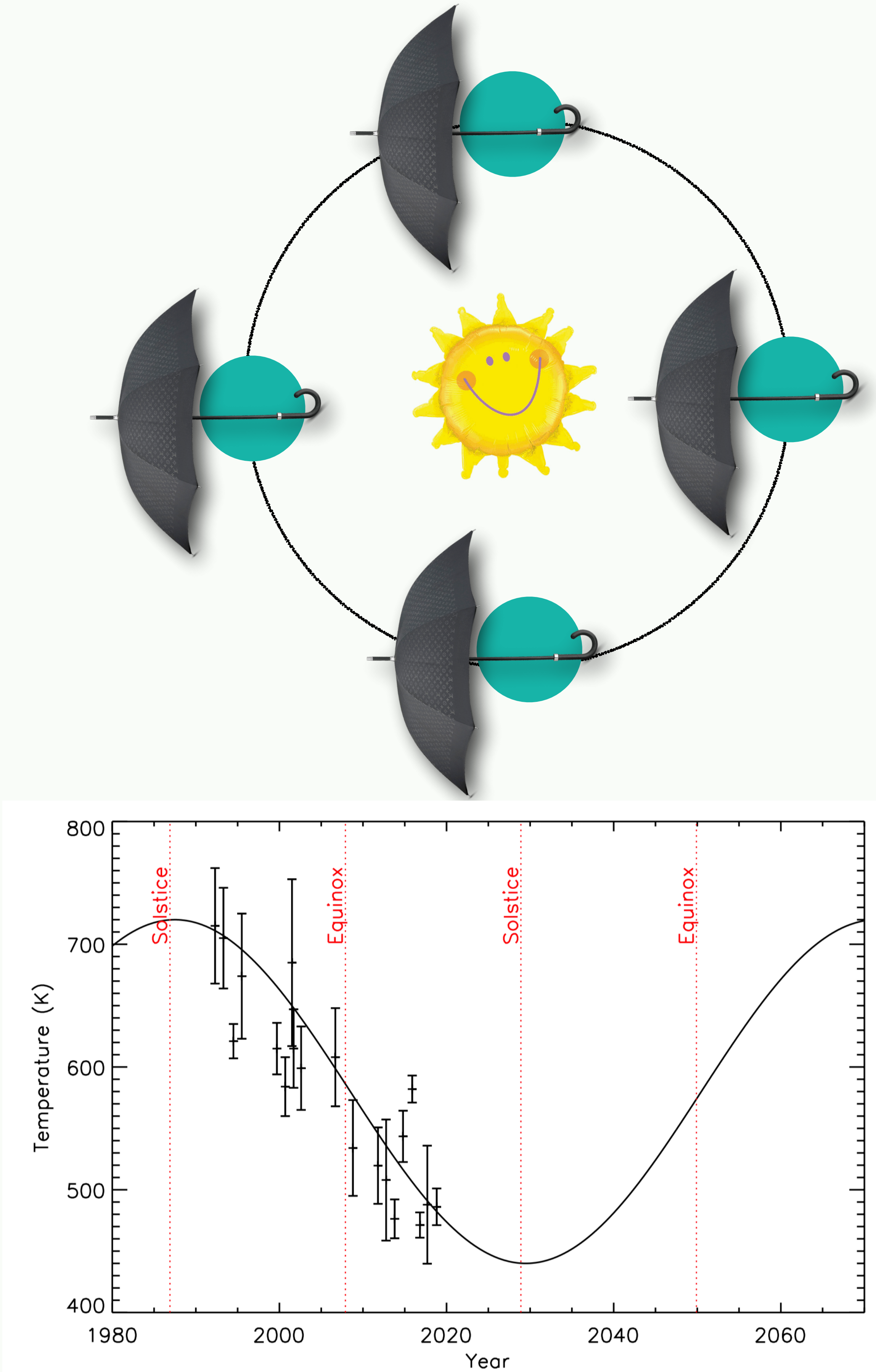


Melin et al., (2019)

Geometric Season

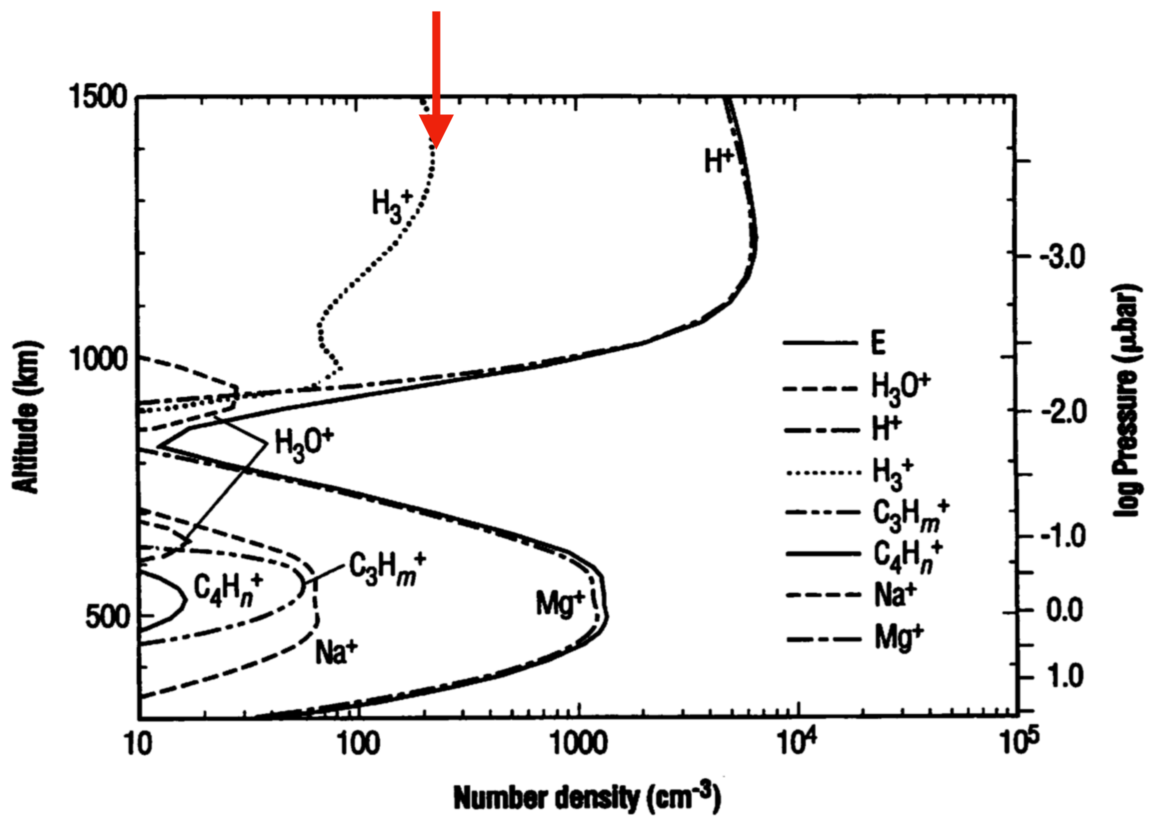
Magnetic Season



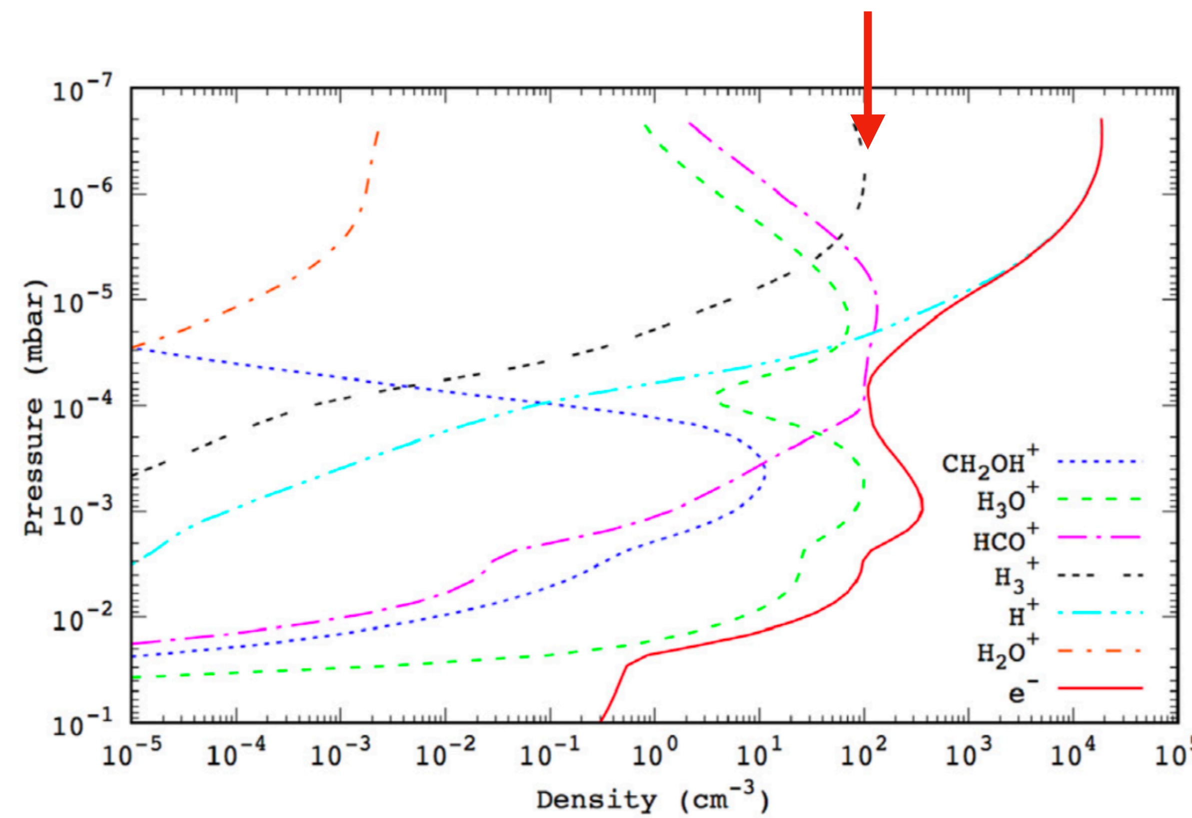


H_3^+ at Neptune

What do we expect to observe?



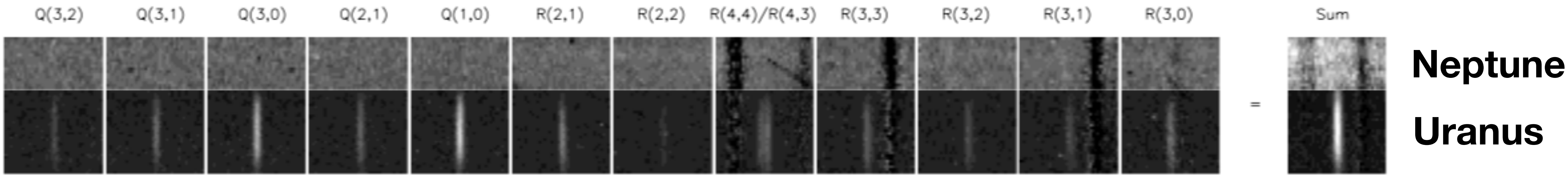
Lyons et al. (1995)



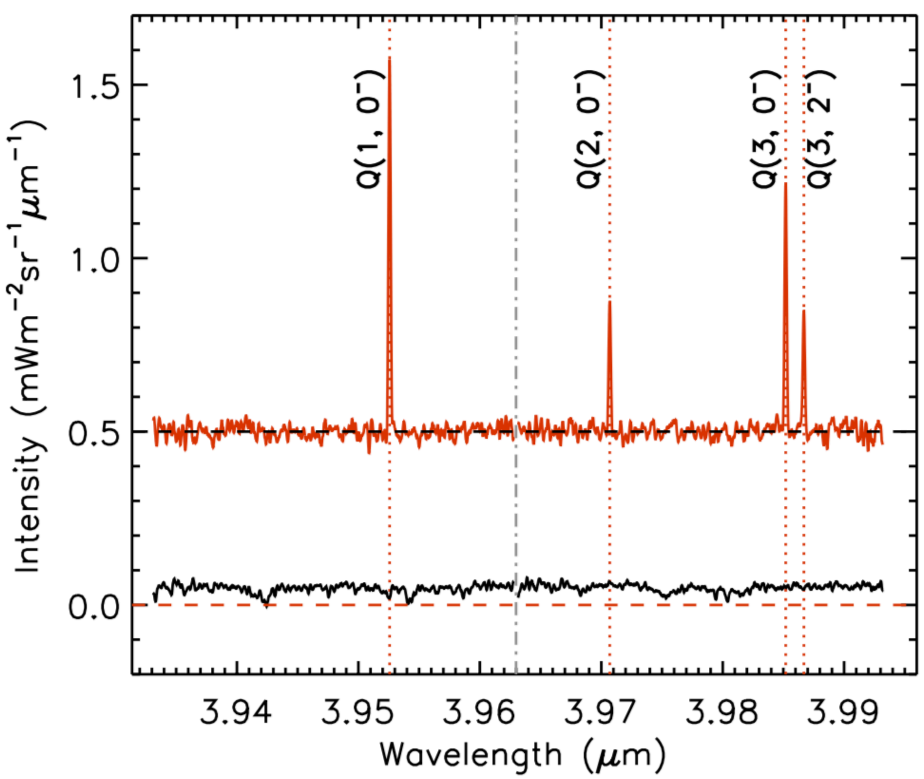
Dobrijevica et al. (2020)

Given a H_3^+ peak density of 100 ions per cubic centimetre and If the temperature structure is the same as in 1989 then H_3^+ will be easily detectable from Neptune with existing ground-based telescopes

H_3^+ at Neptune



Keck NIRSPEC - Melin et al. (2011)



NASA IRTF iSHELL
Melin et al. (2018)

Models underestimate density

OR

The upper atmosphere of Neptune has cooled since Voyager 2 (like Uranus!?)

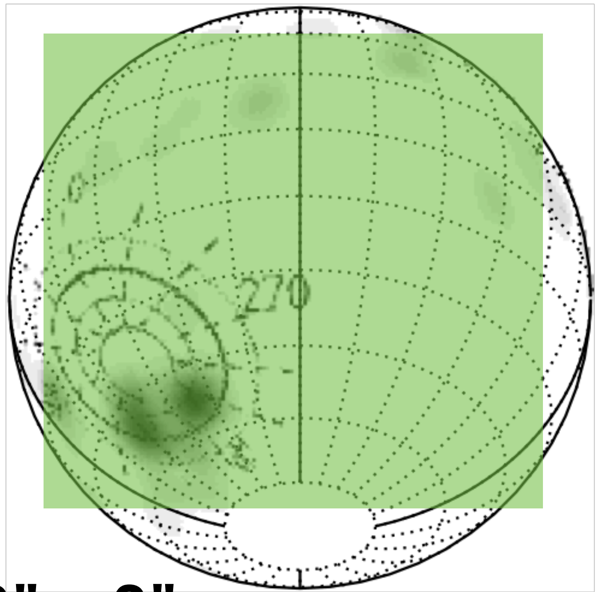
See Moore et al. presentation at the Wednesday splinter meeting

Pressing questions

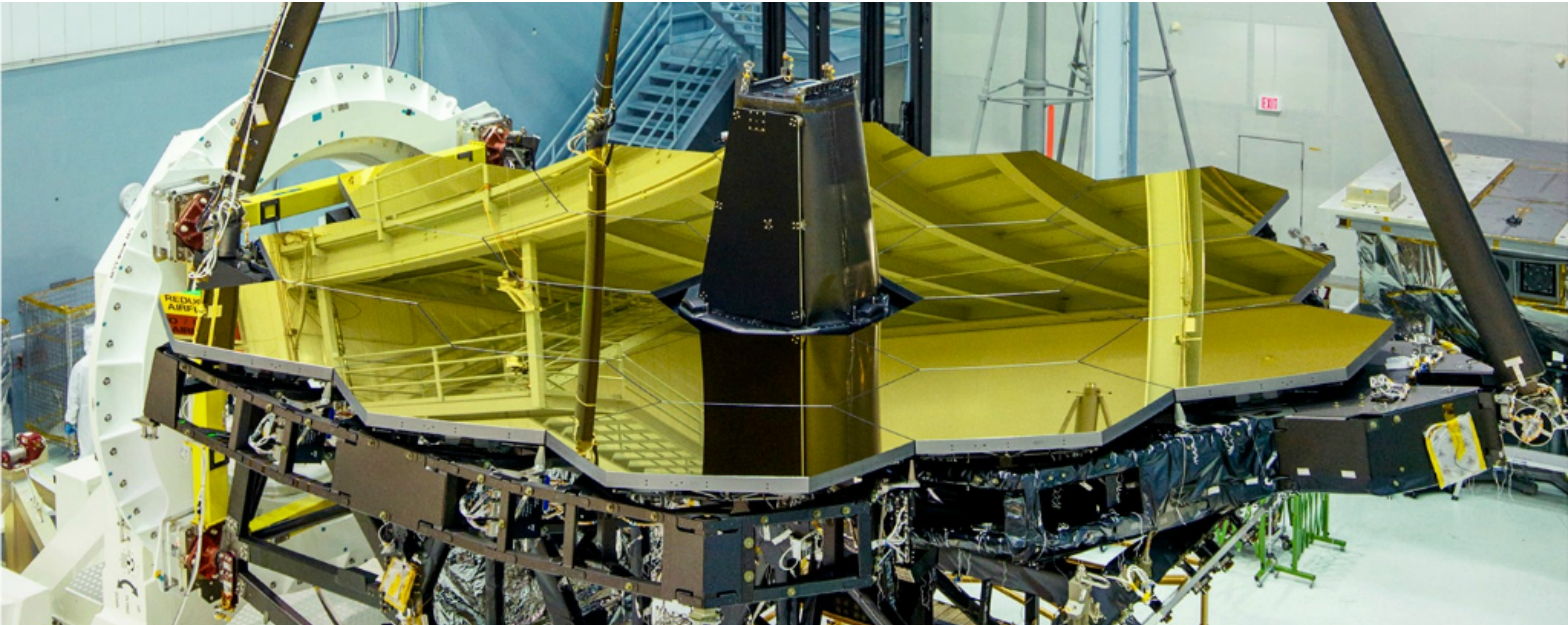
- The Energy Crisis remains - what drives this heating?
- Why are the upper atmospheres of Uranus and Neptune so very different? The upper atmosphere of the giant planets are all very different.
- What is the nature of the interaction between the ionospheres of the ice giants and their magnetospheres? How important is auroral Joule heating? Heating by breaking of gravity waves?
- What drives long-term changes in the temperature of the upper atmosphere of Uranus?
- We need to detect H_3^+ at Neptune!

James Webb Space Telescope

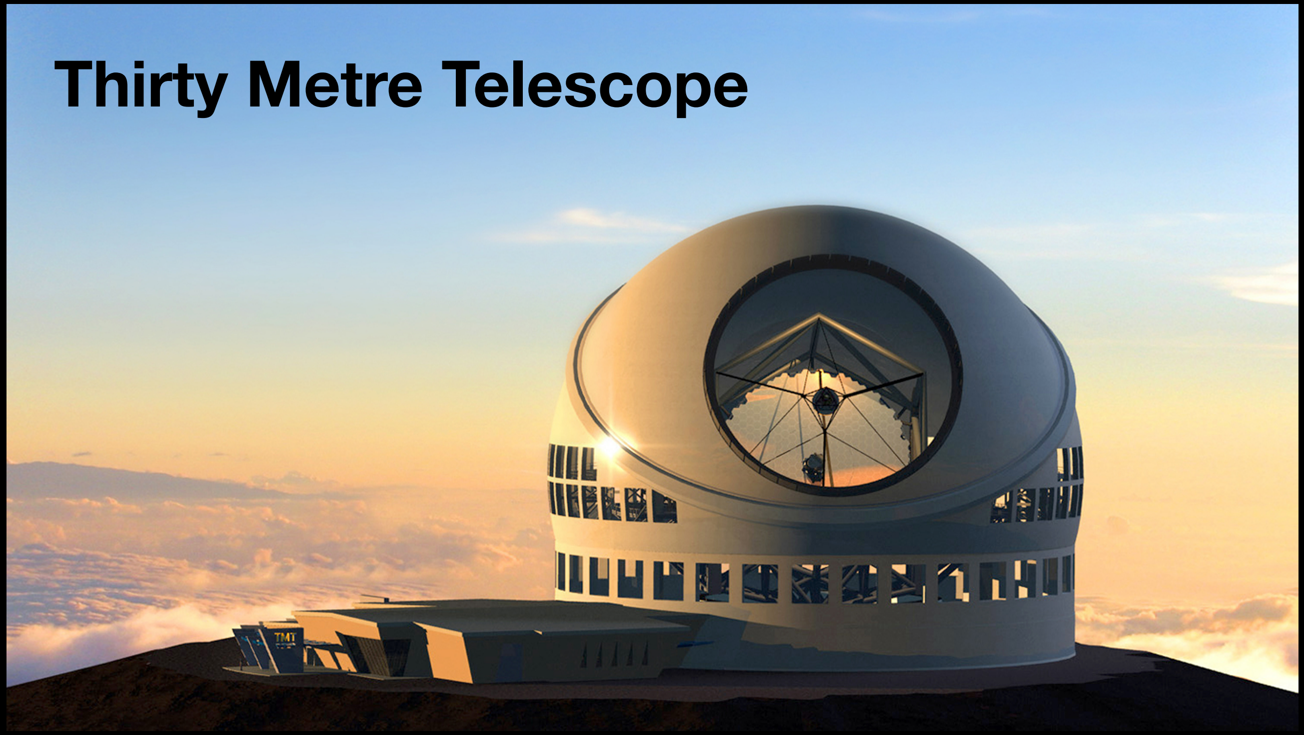
- Launch in March 2021
- High sensitivity and spatial resolution, medium spectral resolution
- NIRSPEC instrument offers 3" x 3" FOV - perfect for Uranus - global mapping of H_3^+
- Uranus NIRSPEC and MIRI observations are in the Guaranteed Time Observing (GTO) programme

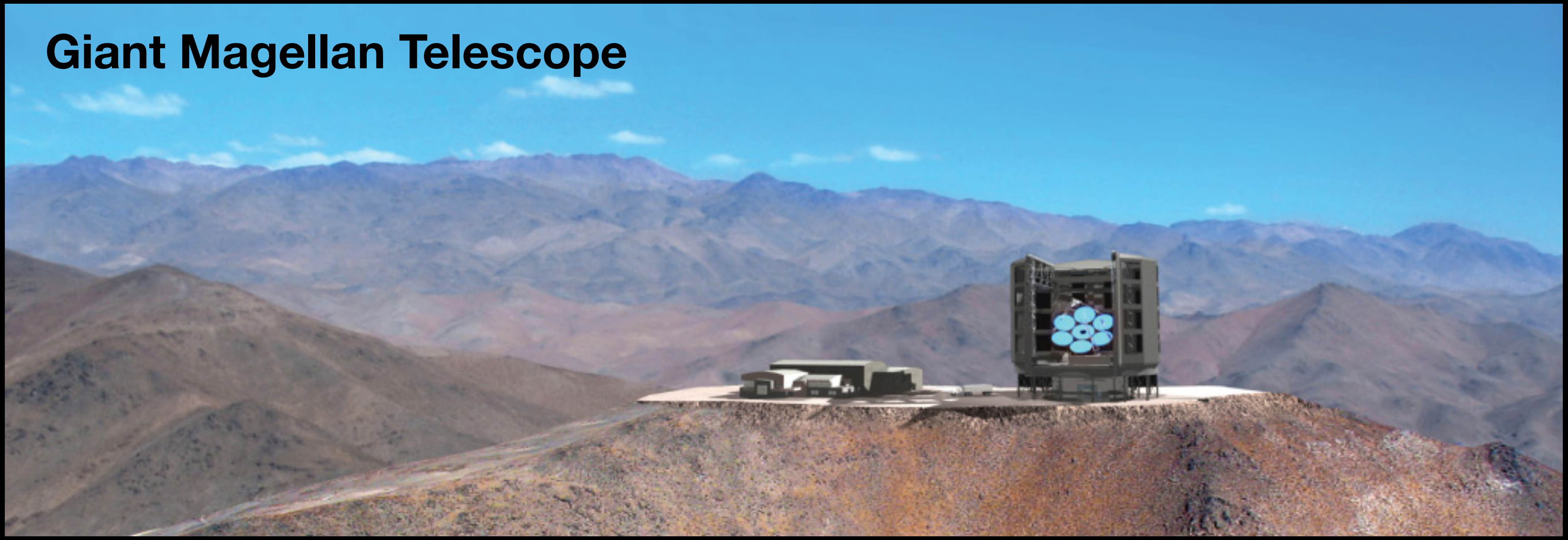


3" x 3"



30 m (100 ft) Telescopes





Conclusions

- The ionosphere is the interface between the atmosphere and the magnetosphere, enabling energy transfer between the two systems

- The upper atmosphere of Uranus has been cooling for 27 years, longer than the nominal season of 21 years. One of kind dataset, detailing behaviour unique to Uranus.

- H_3^+ remains undetected at Neptune :-(

- To truly understand ice giants we need a dedicated mission of exploration!

XXXII. *Account of a Comet. By Mr.* Herſchel, *F. R. S.; communicated by Dr.* Watſon, *Jun. of* Bath, *F. R. S.*

Read April 26, 1781.

ON Tueſday the 13th of March, between ten and eleven in the evening, while I was examining the ſmall ſtars in the neighbourhood of H Geminorum, I perceived one that appeared viſibly larger than the reſt: being ſtruck with its uncommon magnitude, I compared it to H Geminorum and the ſmall ſtar in the quartile between Auriga and Gemini, and finding it ſo much larger than either of them, ſuſpected it to be a comet.