NASA IRTF iSHELL, 2019

The upper atmospheres of the ice giants

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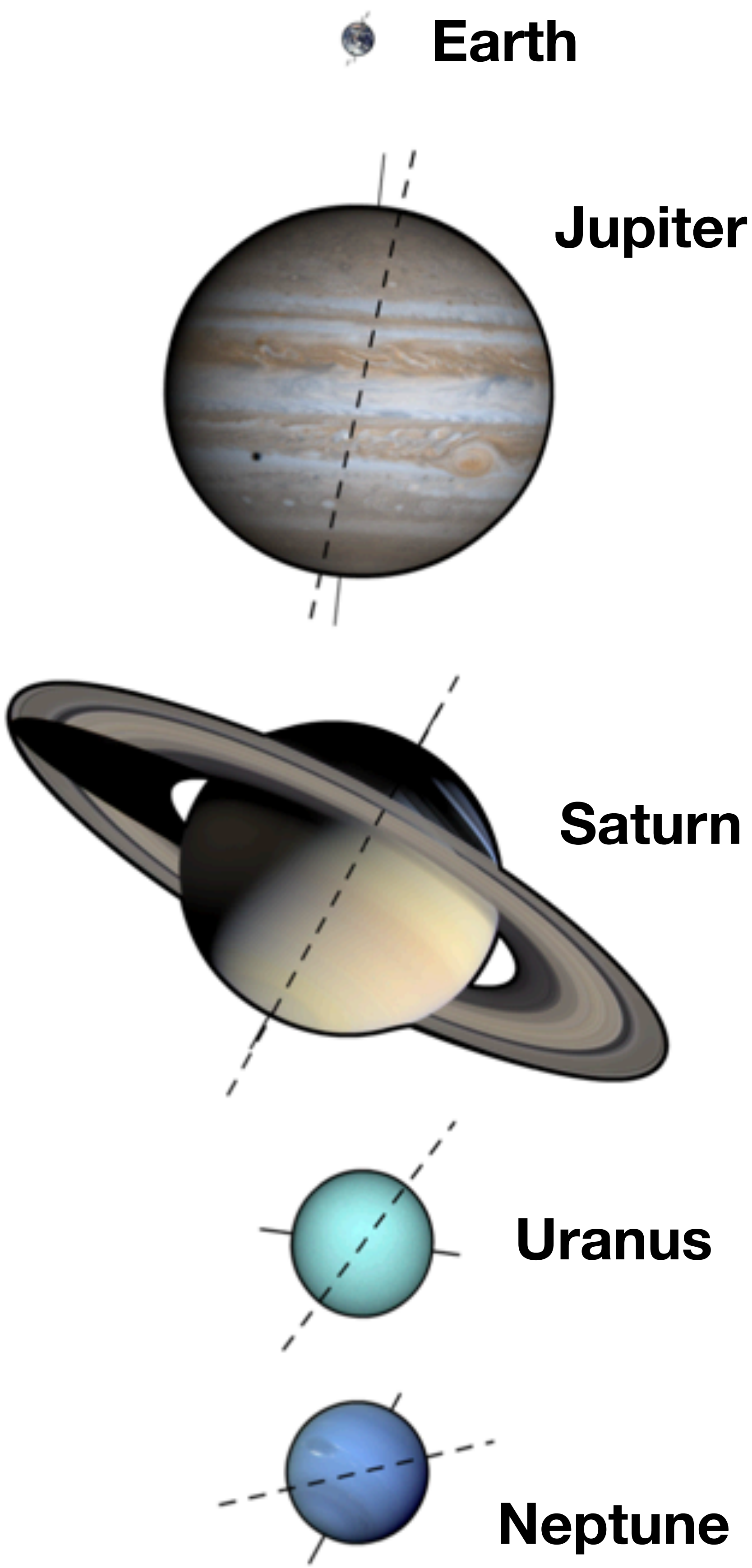
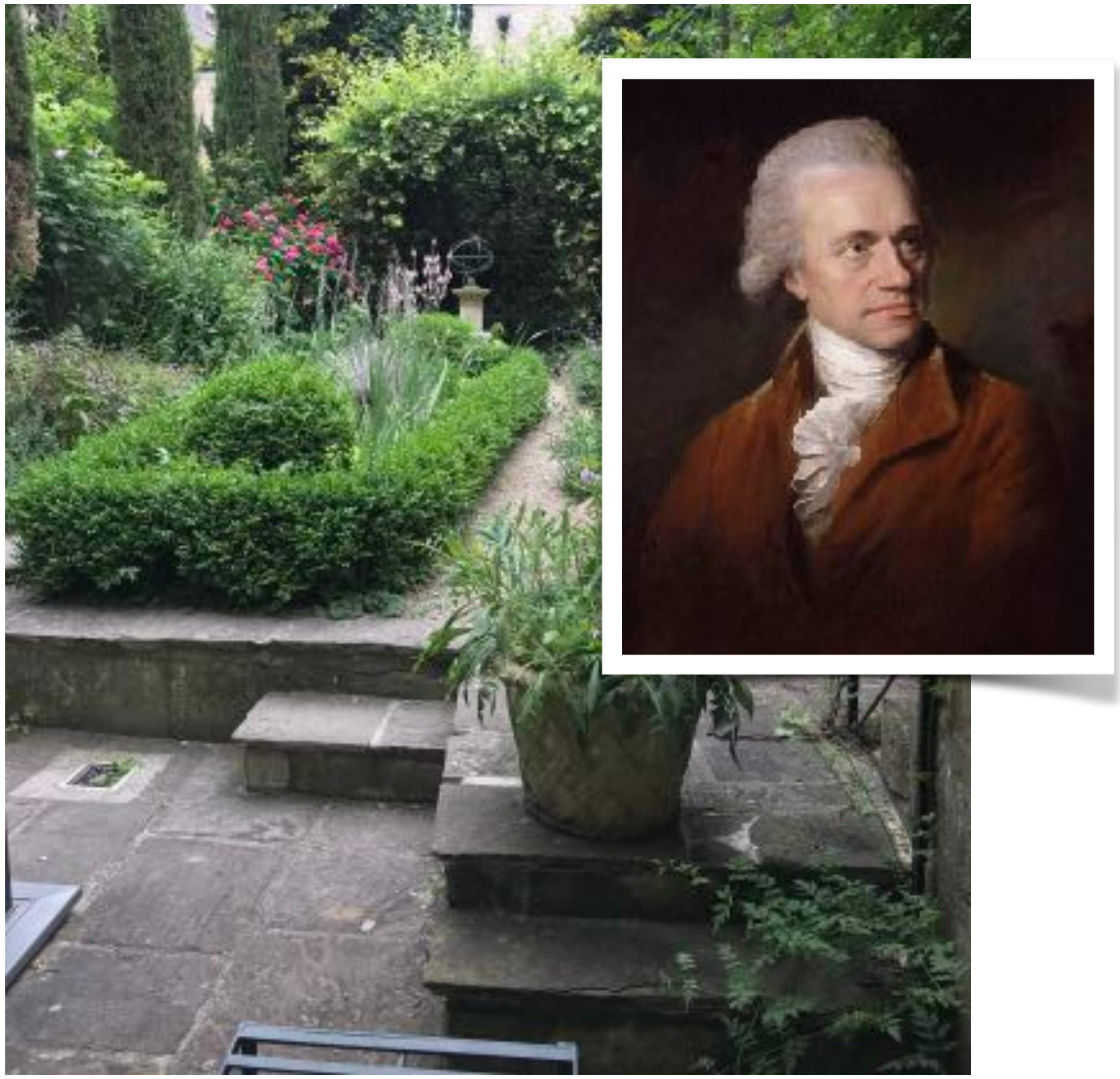


The Ice Giants

- Far away from the Sun, cold temperatures
  Uranus ~19 AU
  Neptune ~30 AU
- Dominated by hydrogen and helium
- Both Neptune and Uranus about 4 times the size of the Earth
- Highly offset magnetic fields, with quadruple and octopod components (i.e. not just a dipole)
- This size and type of planet is common throughout the universe



[492]

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

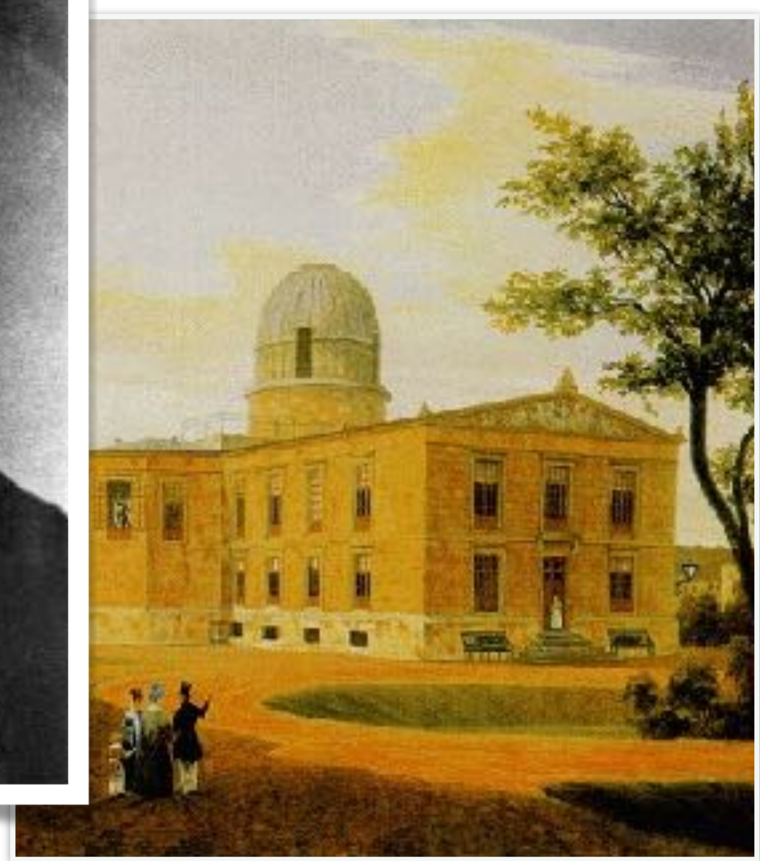
Discovery of Uranus

- First planet to be discovered since the antiquities
- Worked with his sister Caroline to make a number of discoveries
- Chance observation by William Hershel in 1781, which made him a superstar
- Build the 40-foot telescope in Slough, paid for by King George III

Discovery of Neptune

TABLES
ASTRONOMIQUES
PUBLIÉES
PAR LE BUREAU DES LONGITUDES DE FRANCE,
CONTENANT
LES TABLES DE JUPITER, DE SATURNE ET D'URANUS,
CONSTRUITES D'APRÈS LA THÉORIE DE LA MÉCANIQUE CÉLESTE;
PAR M. A. BOUVARD,
Chevalier de l'Ordre royal de la Légion-d'Honneur, Membre de l'Académie royale des Sciences et du Bureau des Longitudes; des Académies royales des Sciences de Turin et de Munich; de la Société astronomique de Londres et de la Société helvétique des Sciences naturelles, etc., etc.

1821 - Alexis Bouvard



1846 - Johann Gottfried Galle

- Alexis Bouvard used Newton's Laws of Motion to predict the positions of Jupiter, Saturn and Uranus - those of Uranus were wildly off

- Adams & Le Verrier both made predictions of where to find the "New Planet"

- Neptune first observed on 24 Sept 1846 by Johann Gottfried Galle at the Berlin Observatory

- *"The planet whose place you have [computed] really exists"*
(Galle to Le Verrier)

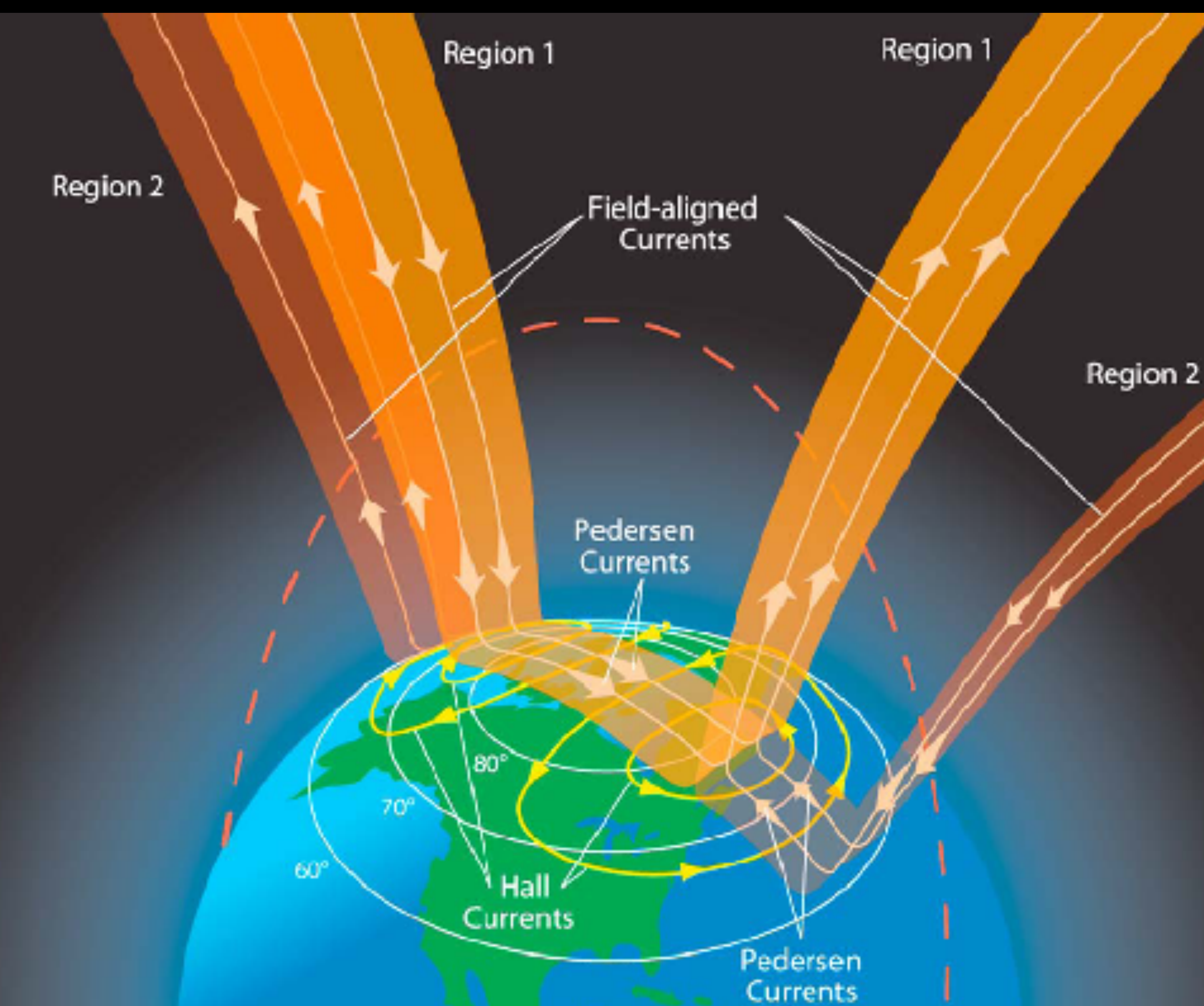
Upper atmosphere - definition

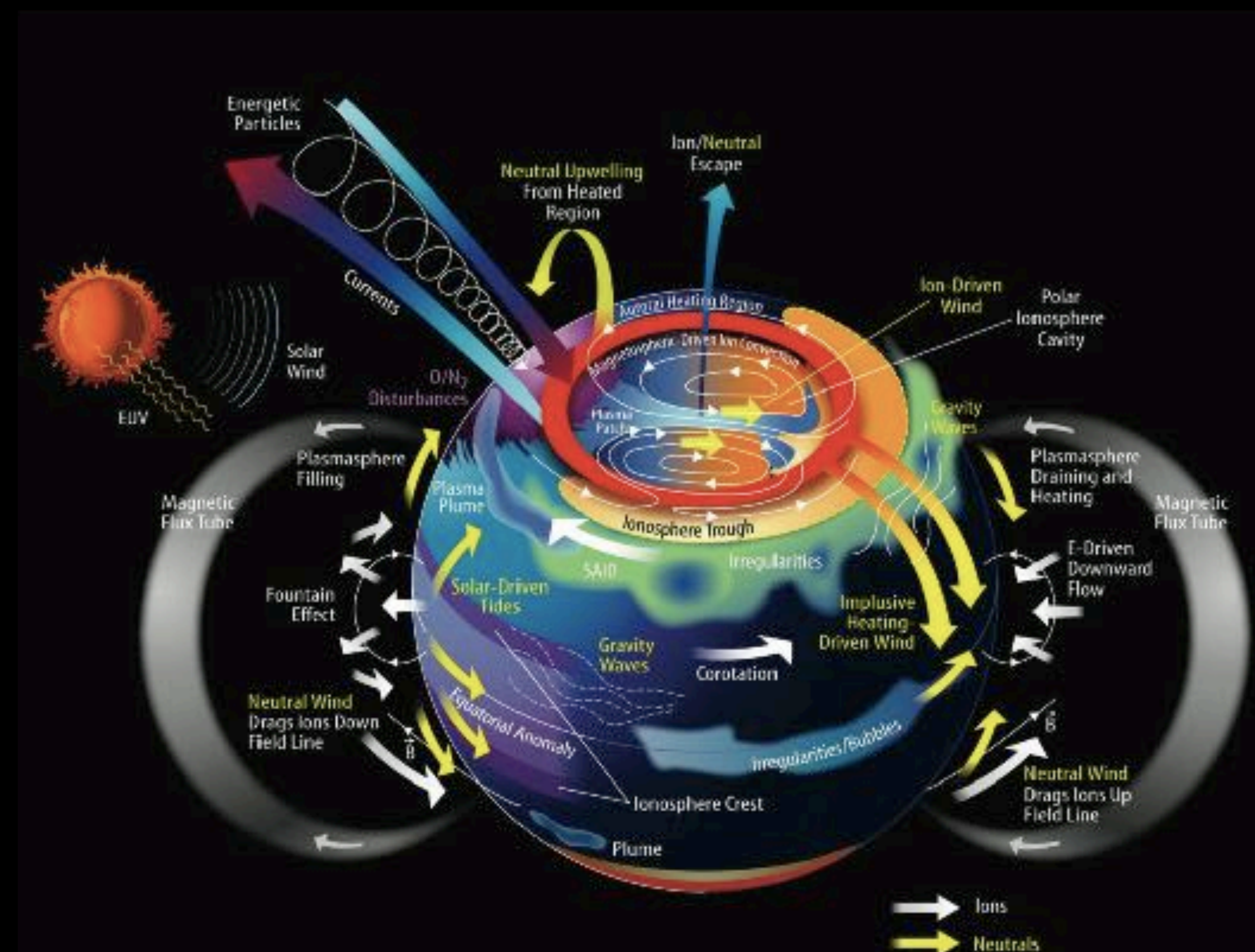
- Situated above the homopause - above which molecular diffusion dominates over eddy diffusion (turbulent mixing)
- Each species is distributed according to its own scale height, dependent on mass. Dominated by light species.
- Low density
- Two basic components: neutral thermosphere and charged particle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





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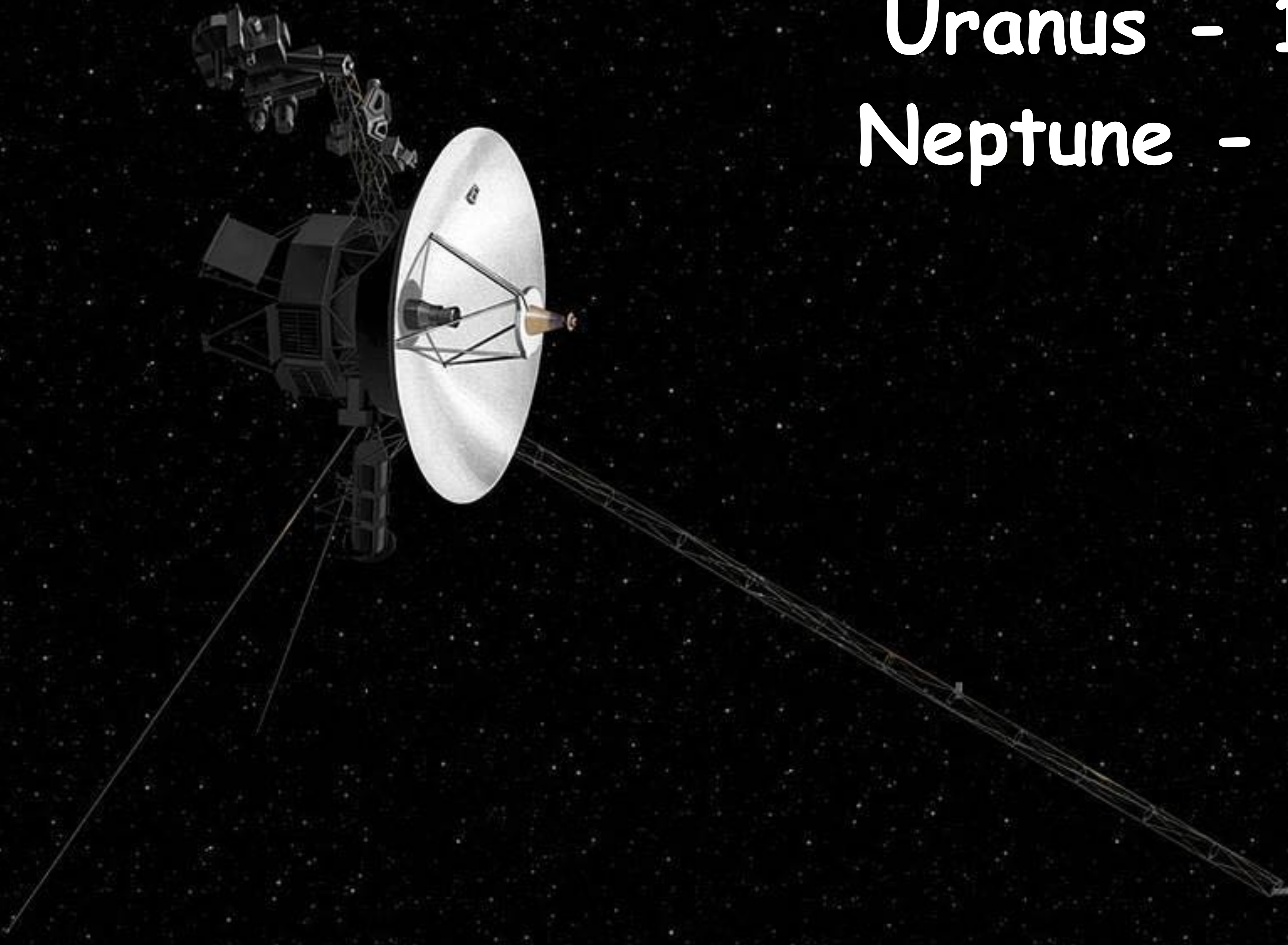
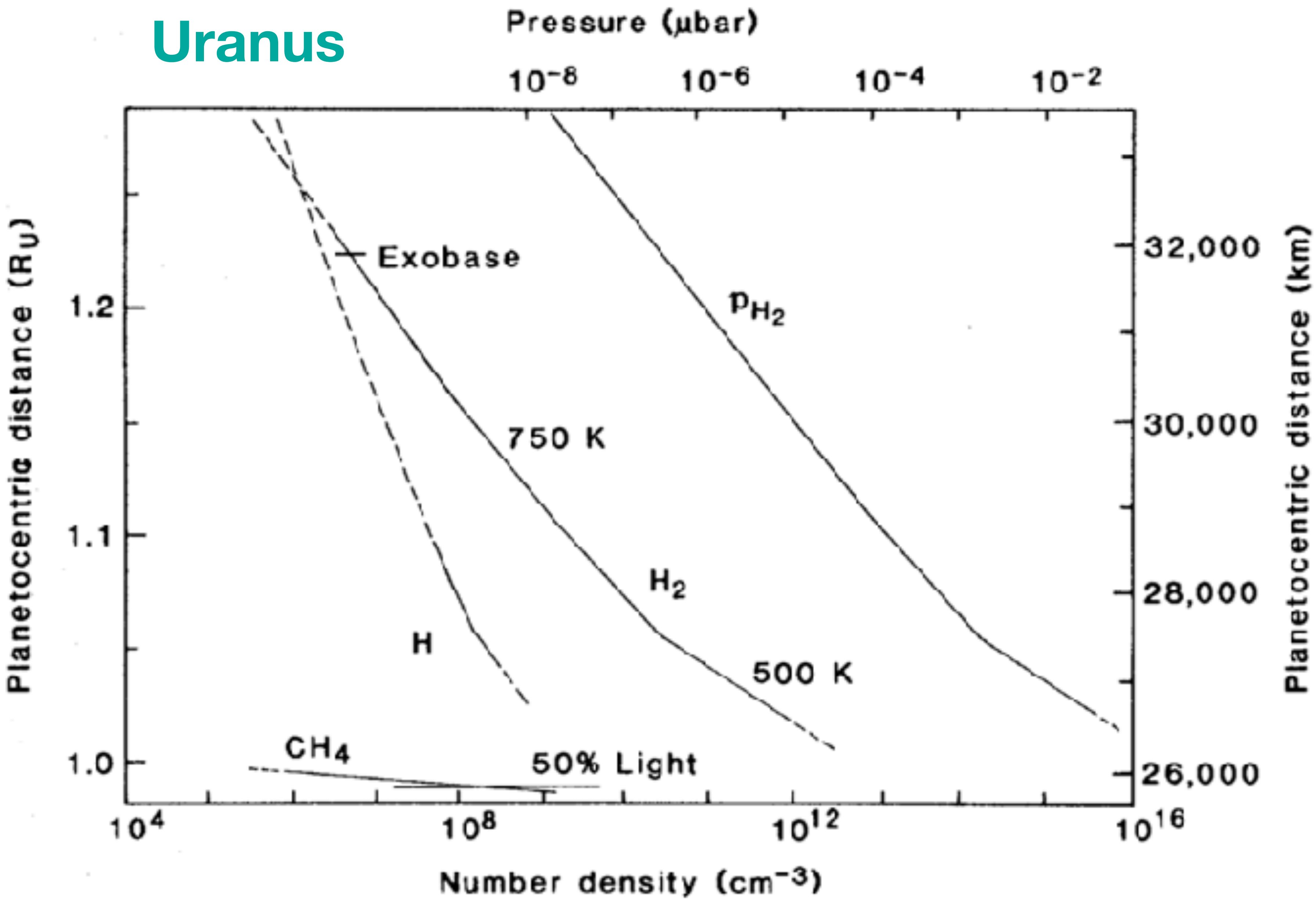
Voyager 2
Uranus - 1986
Neptune - 1989



Atmospheric structure

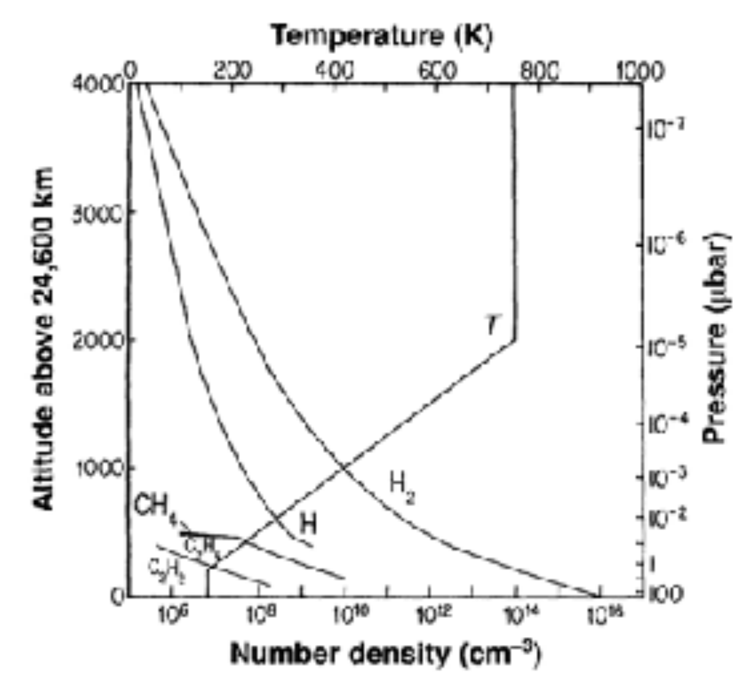
Derived from ultraviolet solar occultations of the upper atmosphere using the Voyager 2 Ultraviolet Spectrometer (UVS)

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

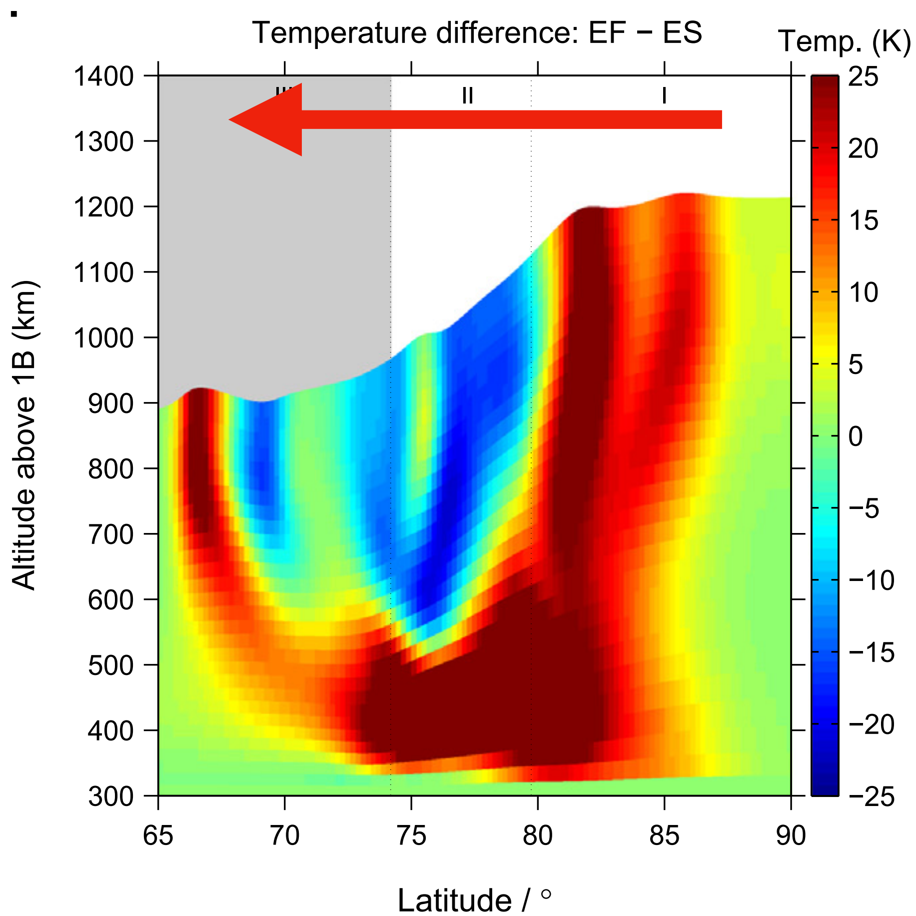
Yelle & Miller (2004)

Observed temperature minus predicted temperature

1. Auroral heating

- The auroral process can inject TW of energy about the magnetic poles
- The giant planets are fast rotators, creating immense Coriolis forces
- How can heat be transported?
- O'Donoghue et al., (2021) suggests it's possible

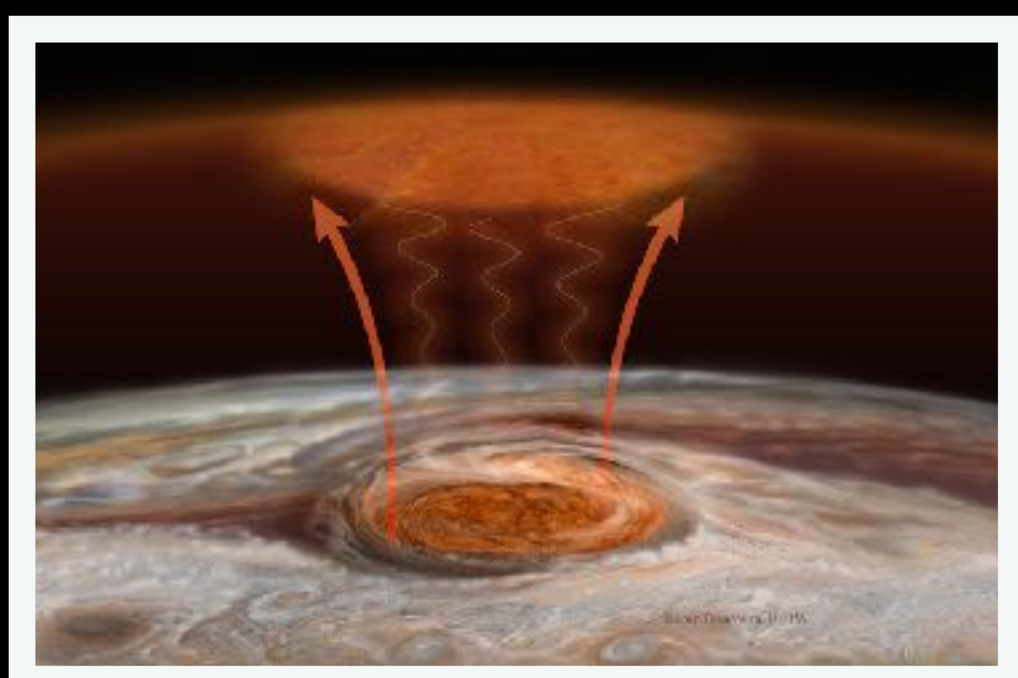
Change in Temperature (K)



Yates et al. (2014)

2. Wave heating

- Turbulent lower atmosphere generates gravity waves that release their energy in the upper atmosphere
- Models unclear on how efficient this process is
- O’Donoghue et al., (2016) observed heating above the Great Red Spot of Jupiter
- Understanding of low-latitude ionosphere remains vague - especially at Uranus and Neptune

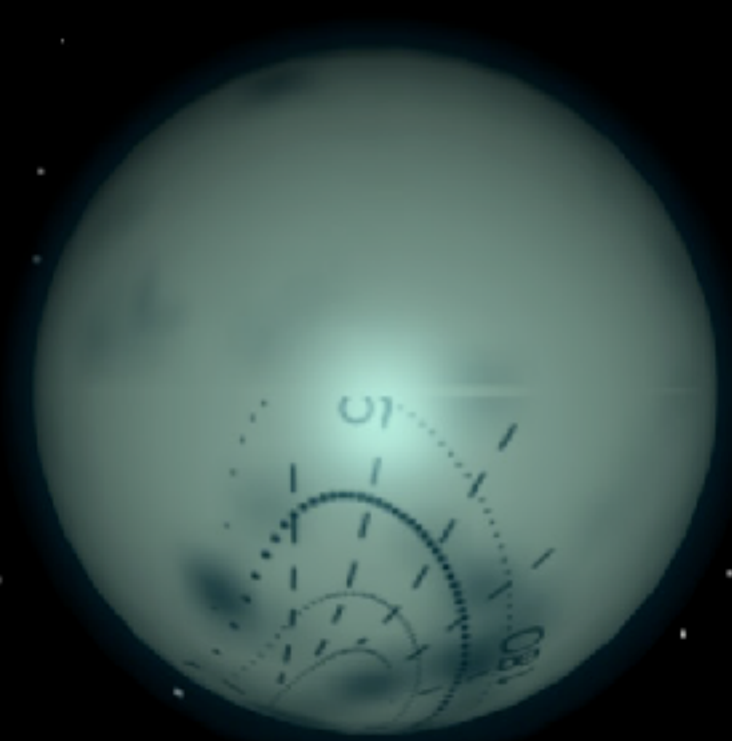


O’Donoghue et al., (Nature, 2016)

Ice giant auroral emissions

Uranus

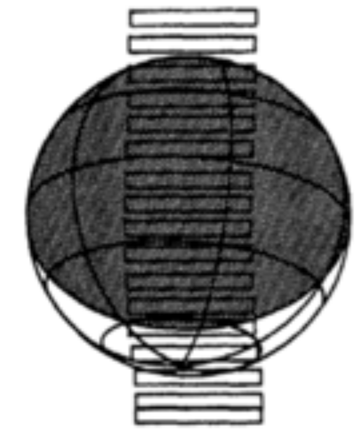
Auroral H_2 emission mapped to equinoctial geometry

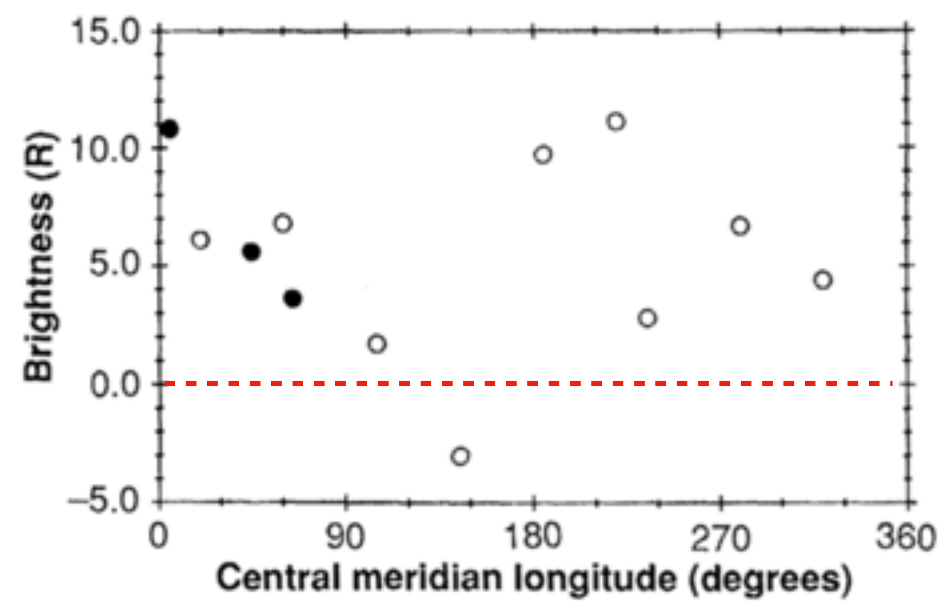


Voyager 2 - Herbert (2009)

Hubble Space Telescope
Lamy et al. (2012, 2017, 2018)

Neptune





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

Energy Solar photons
Energetic particles

Some Very Simple Chemistry (in the Upper Atmosphere)

H & H_2

Excitation

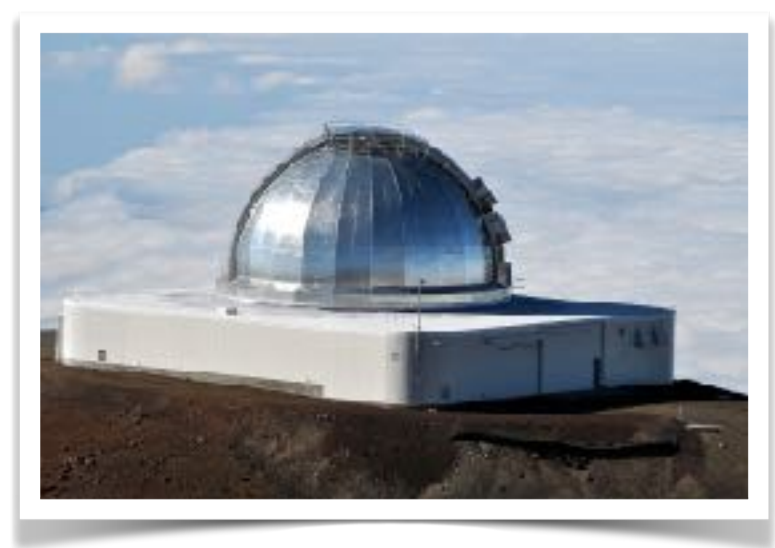
Ultraviolet

Ionization

H_2^+

H_2

H_3^+



Infrared

Infrared

The molecular ion H_3^+

$$H_2^+ + H_2 \longrightarrow H_3^+ + H$$

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

Number density (N) **Temperature** (T)

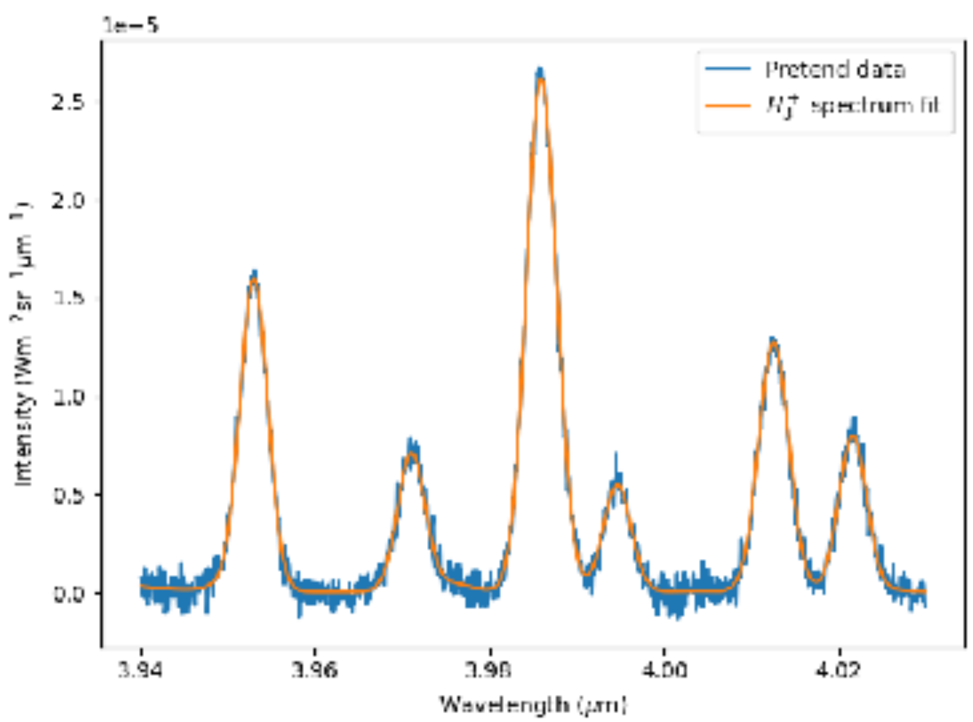
Loss mechanisms

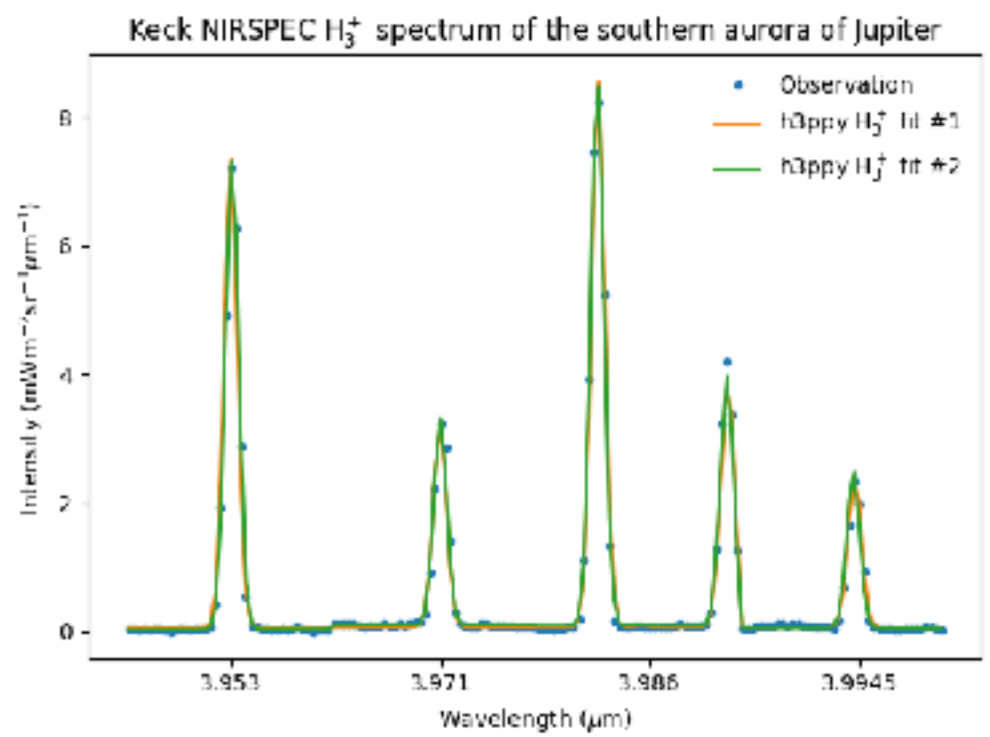
$$H_3^+ + e^- \longrightarrow H_2 + H$$
$$H_3^+ + e^- \longrightarrow H + H + H$$
$$H_3^+ + X \longrightarrow HX^+ + H_2$$

H_3^+ cannot coexist with CH_4

Modelling H_3^+ emissions

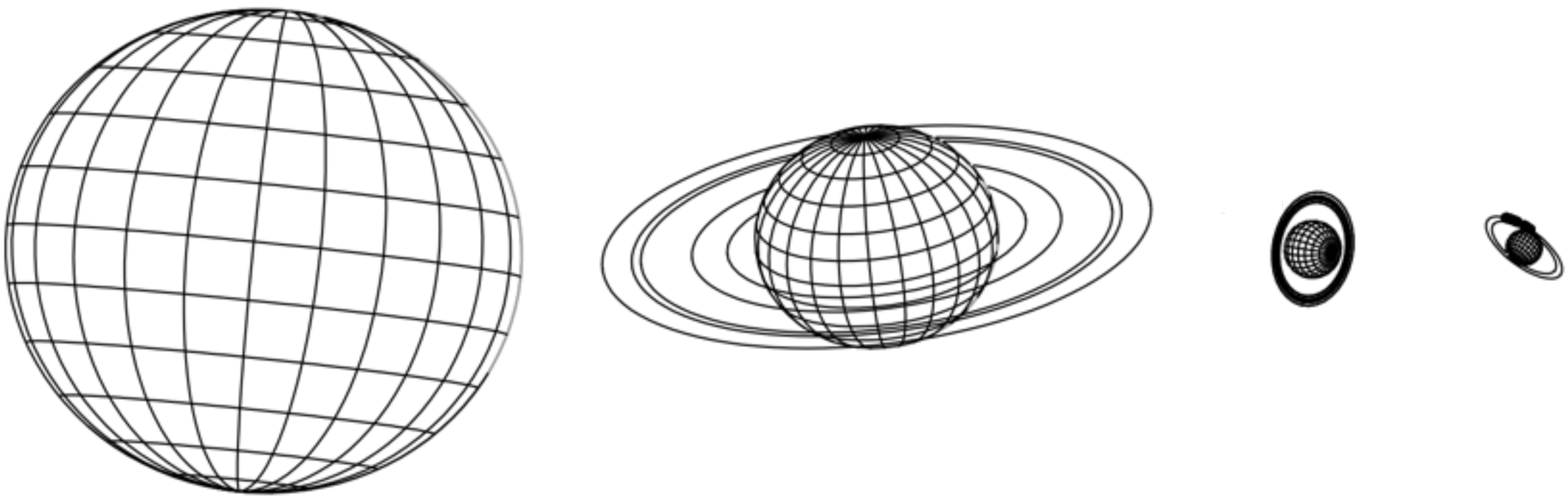
- `h3ppy` - Python 3 package to model and fit observed H_3^+ spectra
- Install: pip install h3ppy
- https://github.com/henrikmelin/h3ppy





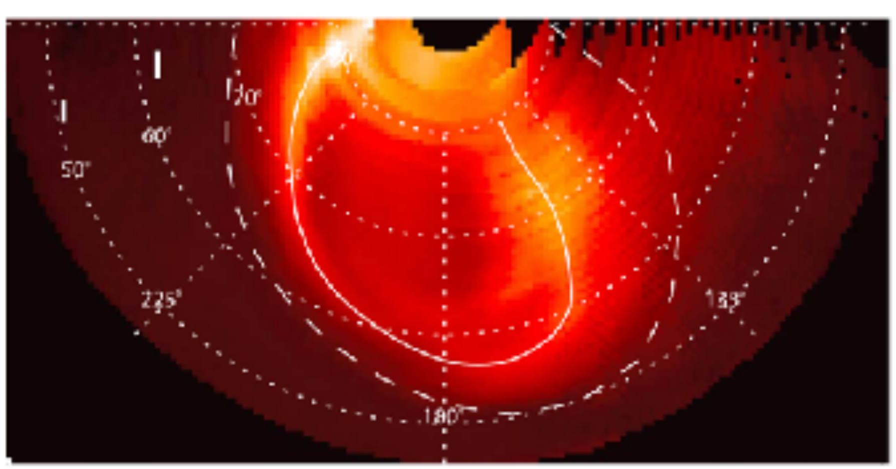
H_3^+ as seen from the Earth

Apparent relative sizes



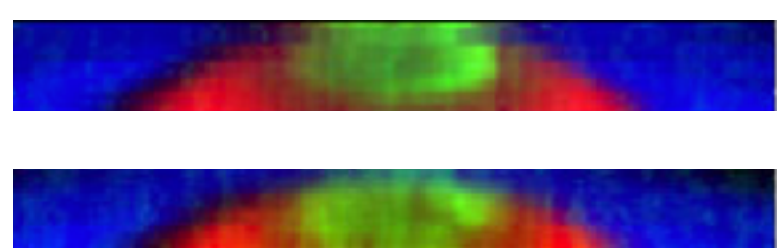
Jupiter **Saturn** **Uranus** **Neptune**

VLT CRIRES



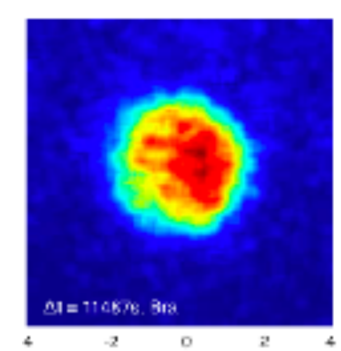
Johnson et al. (2018)

Keck NIRSPEC



Stallard et al. (2019)

Gemini NIRI

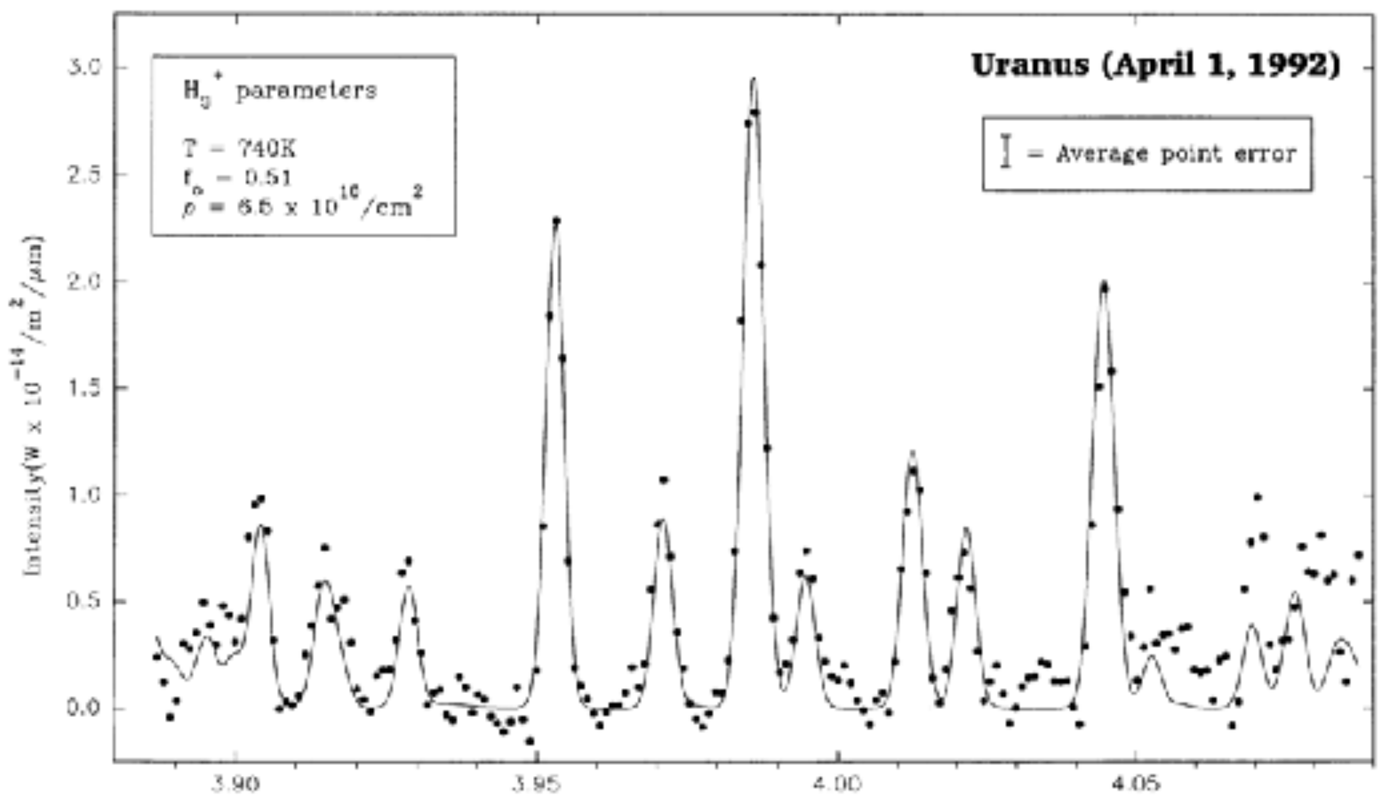


Lamy et al. (2018)

?

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)

First long-term study

Re-analysed all available near-infrared observations of H_3^+ from Uranus, retrieving temperature

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

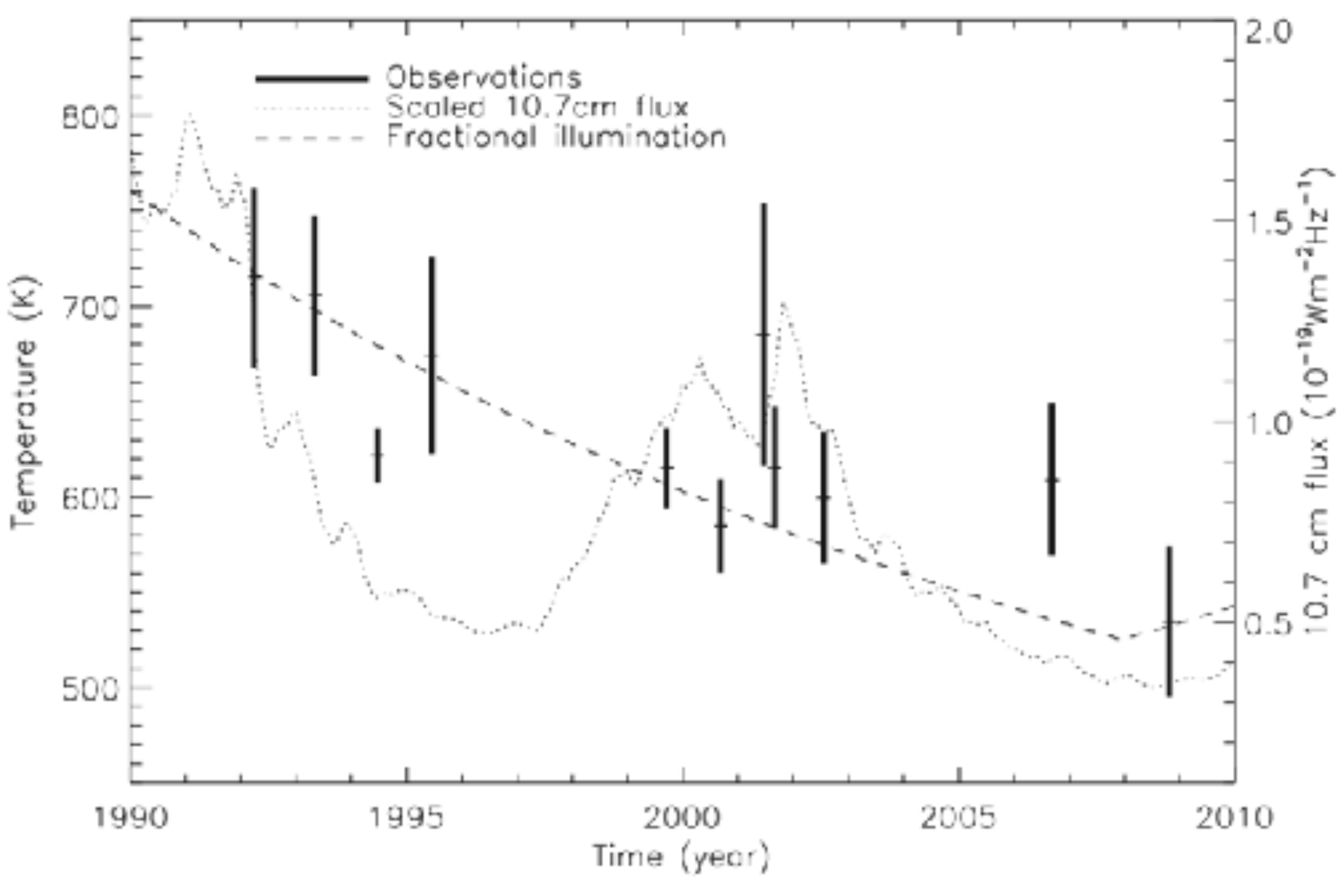
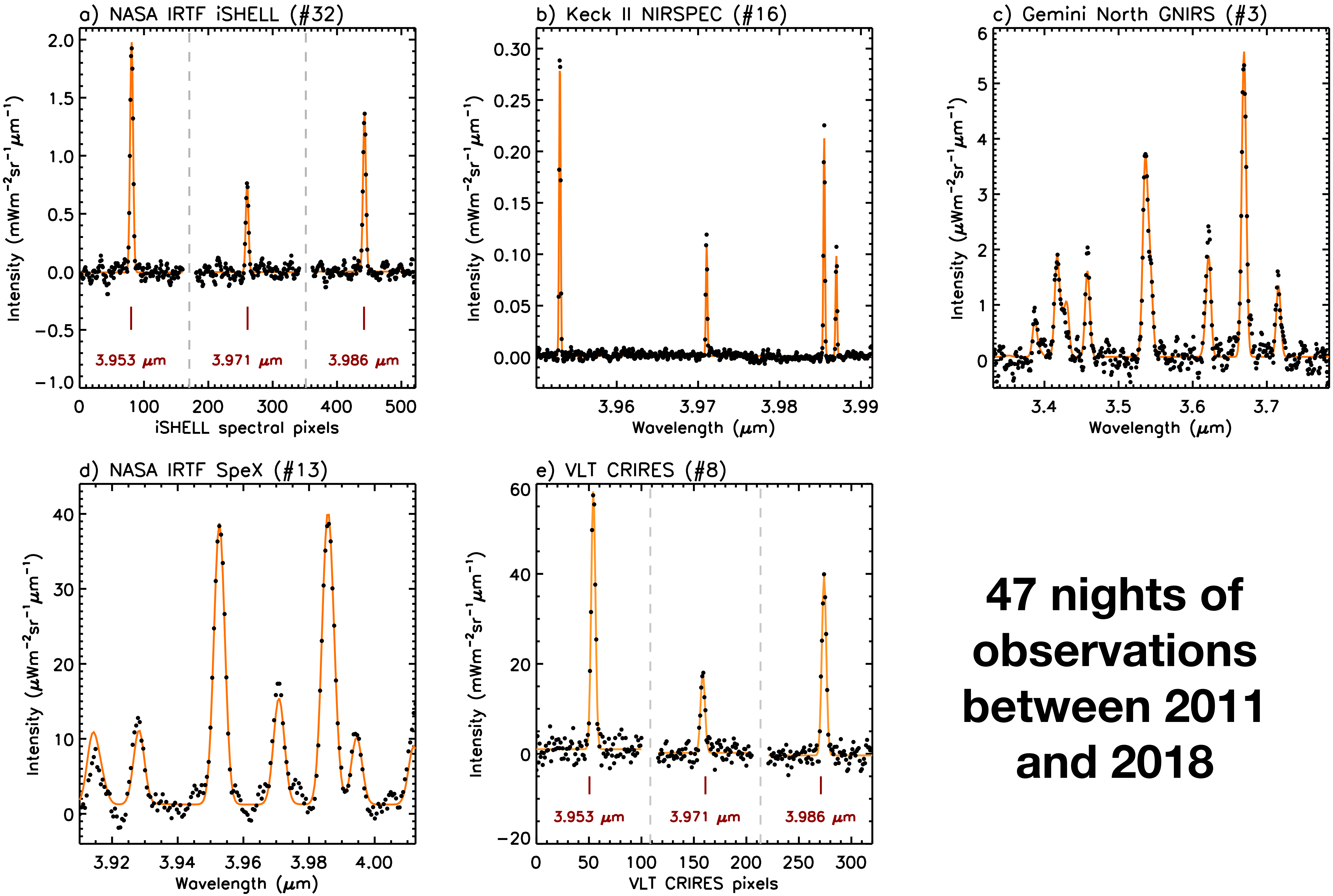


Table 3
The Energy Injected into the Upper Atmosphere by Solar Ultraviolet Radiation Compared to the Radiative Cooling Provided by H_3^+

Run Number	Year	Solar Input (GW)	H_3^+ Cooling (GW)	Ratio
1	1992.3	25.9	222.8	0.12
2	1993.3	19.8	207.1	0.10
3	1994.5	16.0	332.4	0.05
4	1995.5	15.2	160.0	0.10
5	1999.7	26.1	447.7	0.06
6	2000.7	27.5	350.2	0.08
7	2001.5	27.6	207.6	0.13
8	2001.7	29.4	222.2	0.13
9	2002.6	26.9	200.0	0.13
10	2006.7	15.6	152.9	0.10
11	2008.8	14.2	138.4	0.10
Average	...	22.2	240.1	0.10

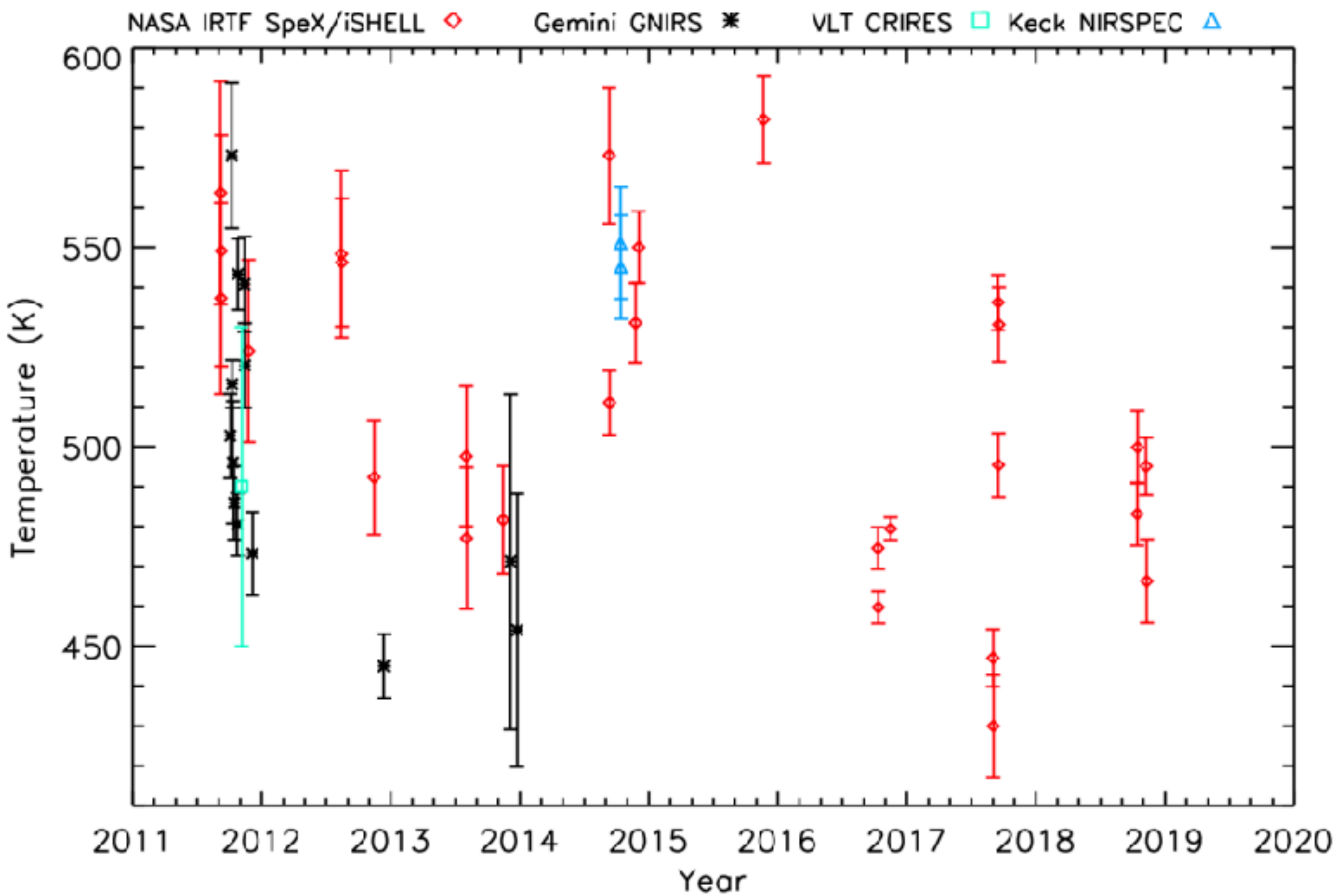
Melin et al., (2011)

New observations of H_3^+ form Uranus



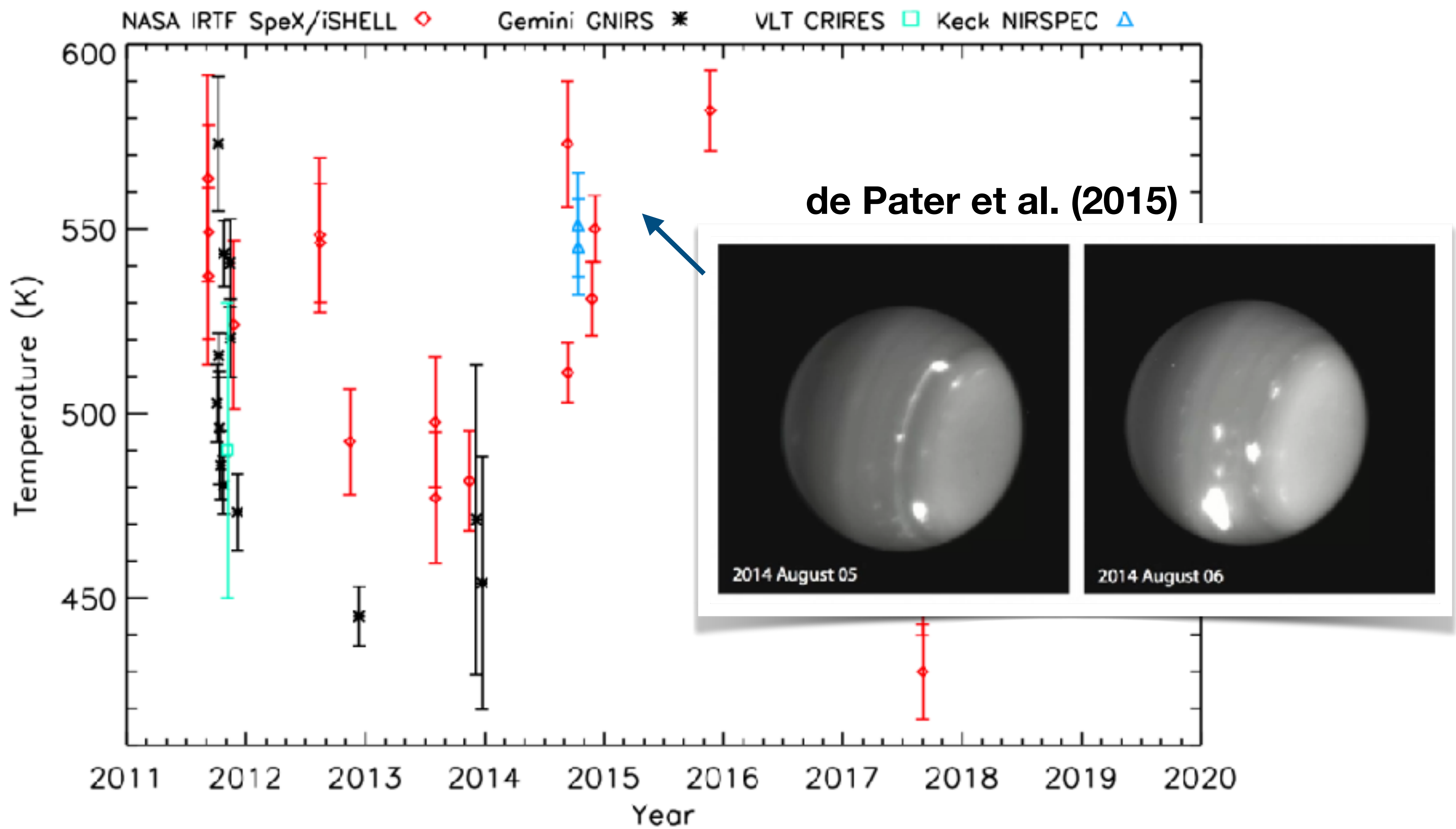
47 nights of observations between 2011 and 2018

New observations



Lots of scatter
2014 & 2015 stands out as hotter than the rest
Calculate yearly averages

New observations



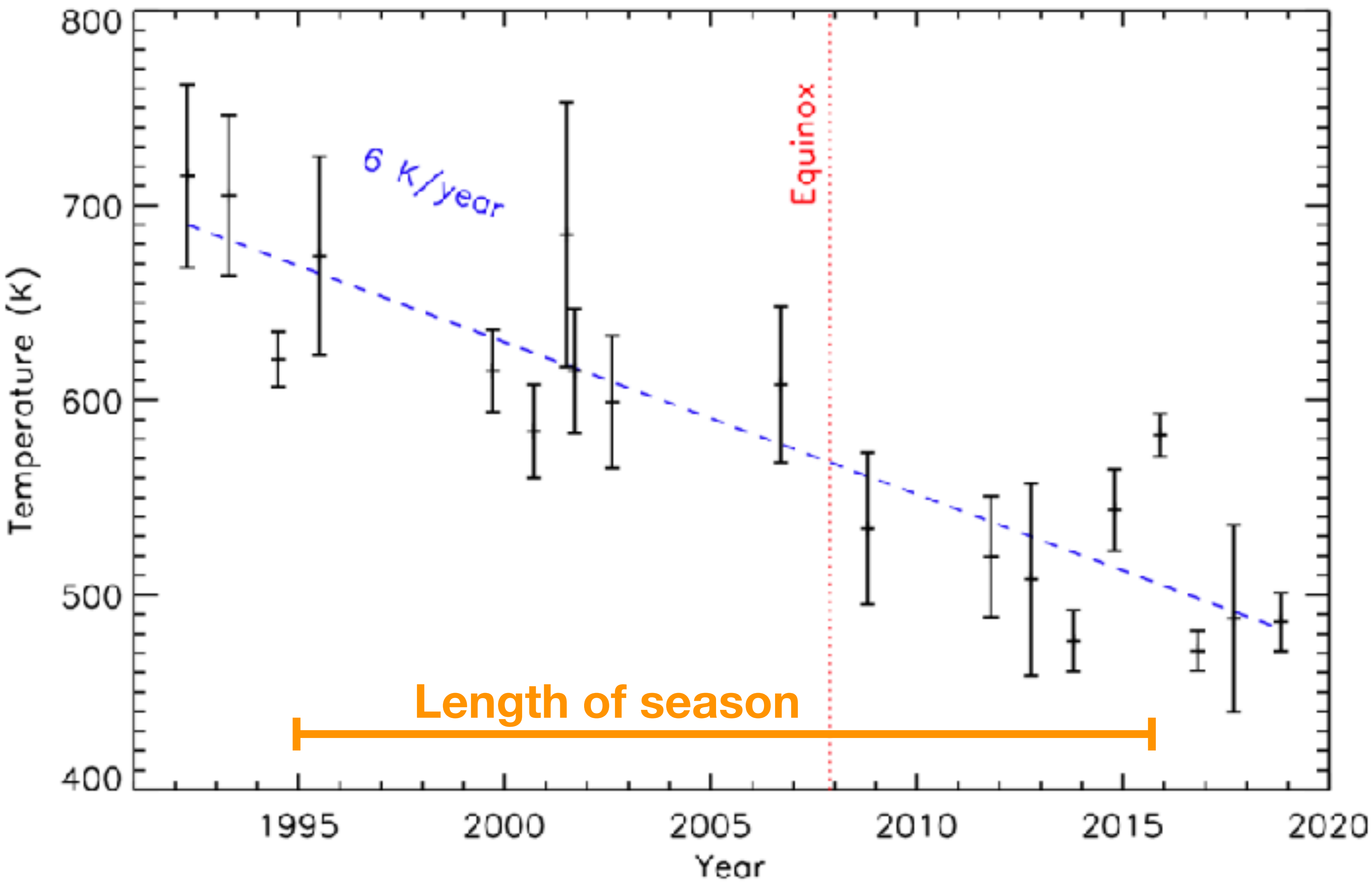
Lots of scatter
2014 & 2015 stands out as hotter than the rest
Calculate yearly averages

Long-term variability

One of a kind long-term dataset

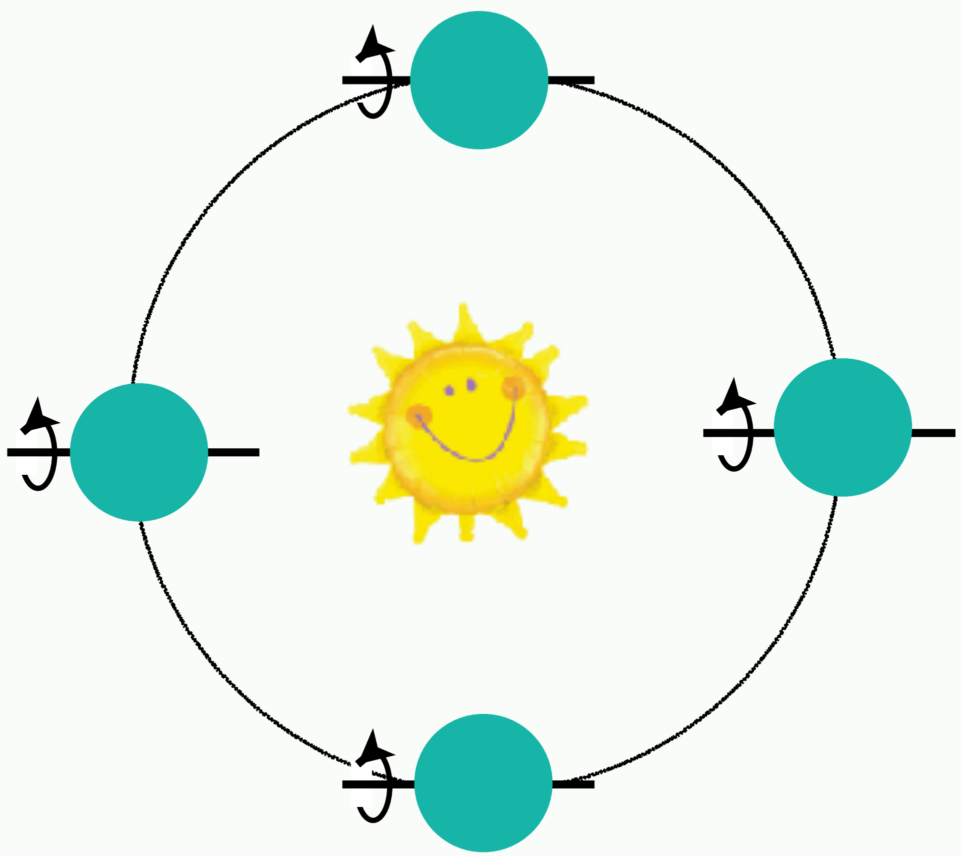
Continuous cooling for 27 years - longer than length of season!

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

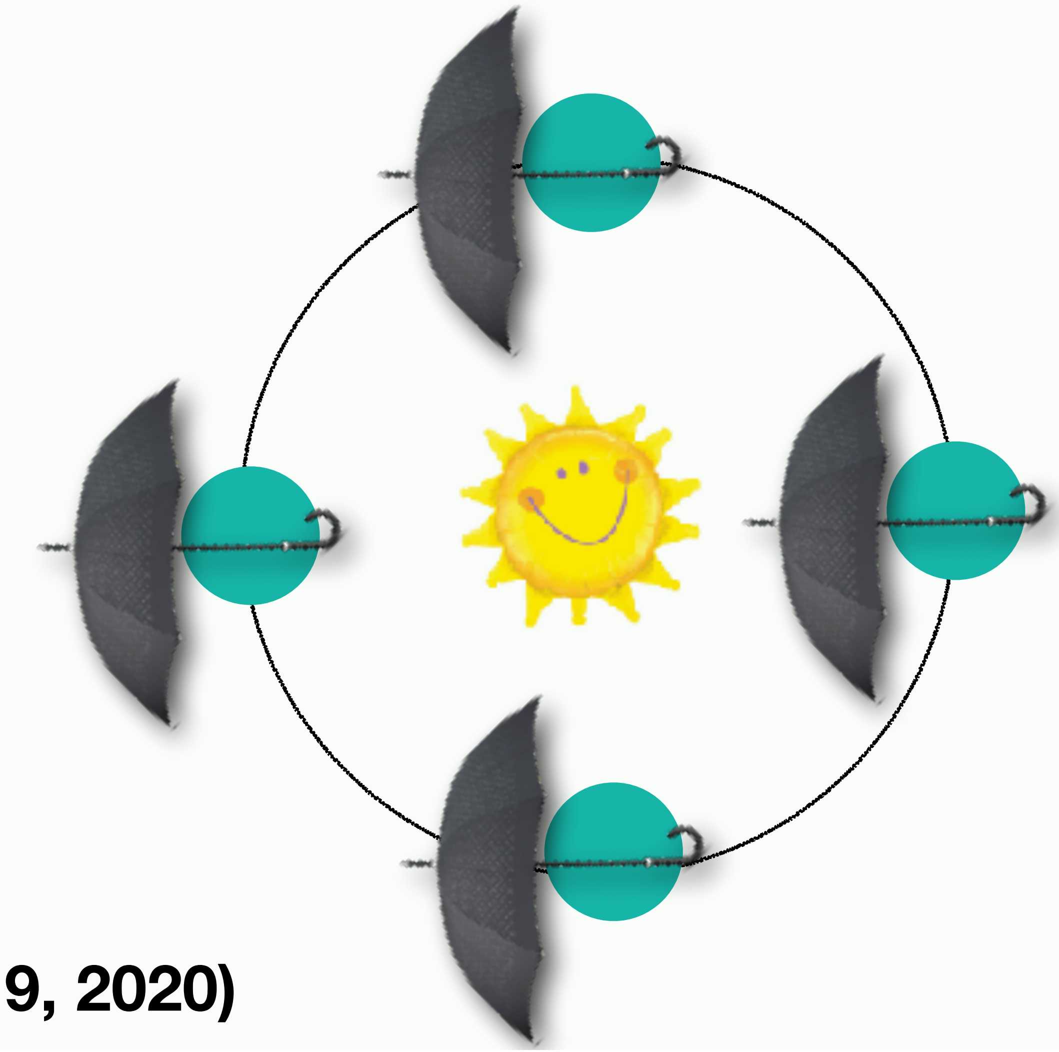


Melin et al., (2019, 2020)

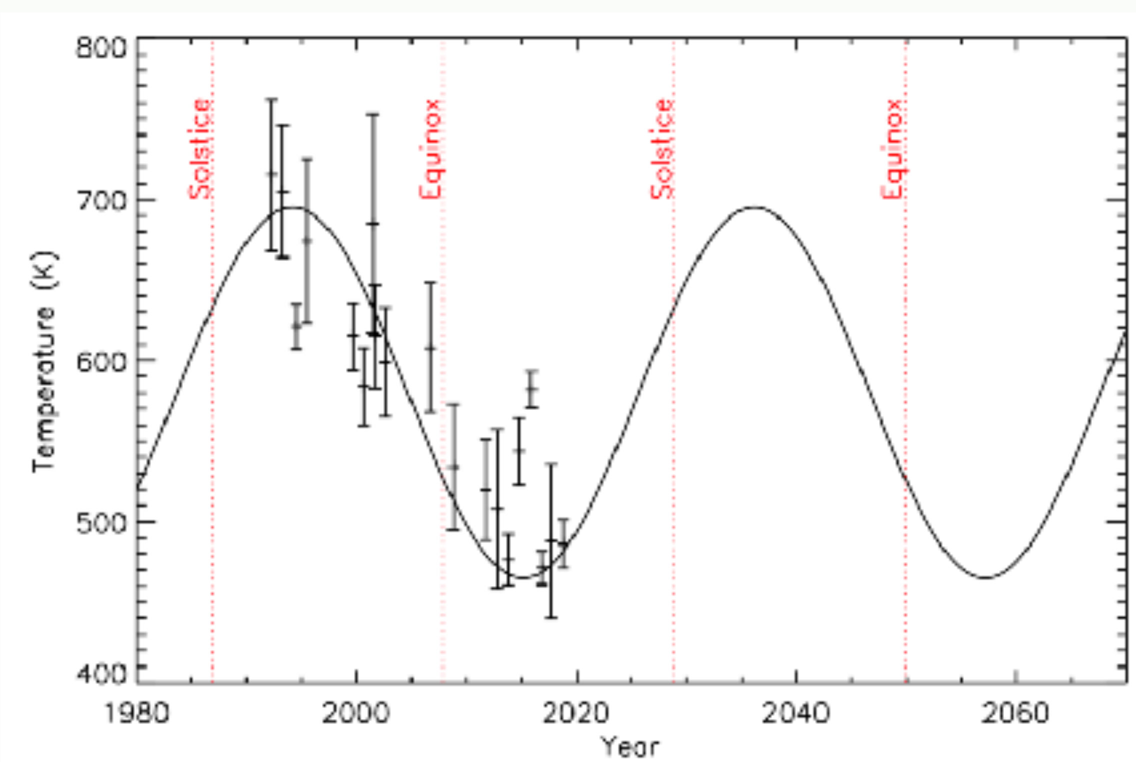
Geometric Season

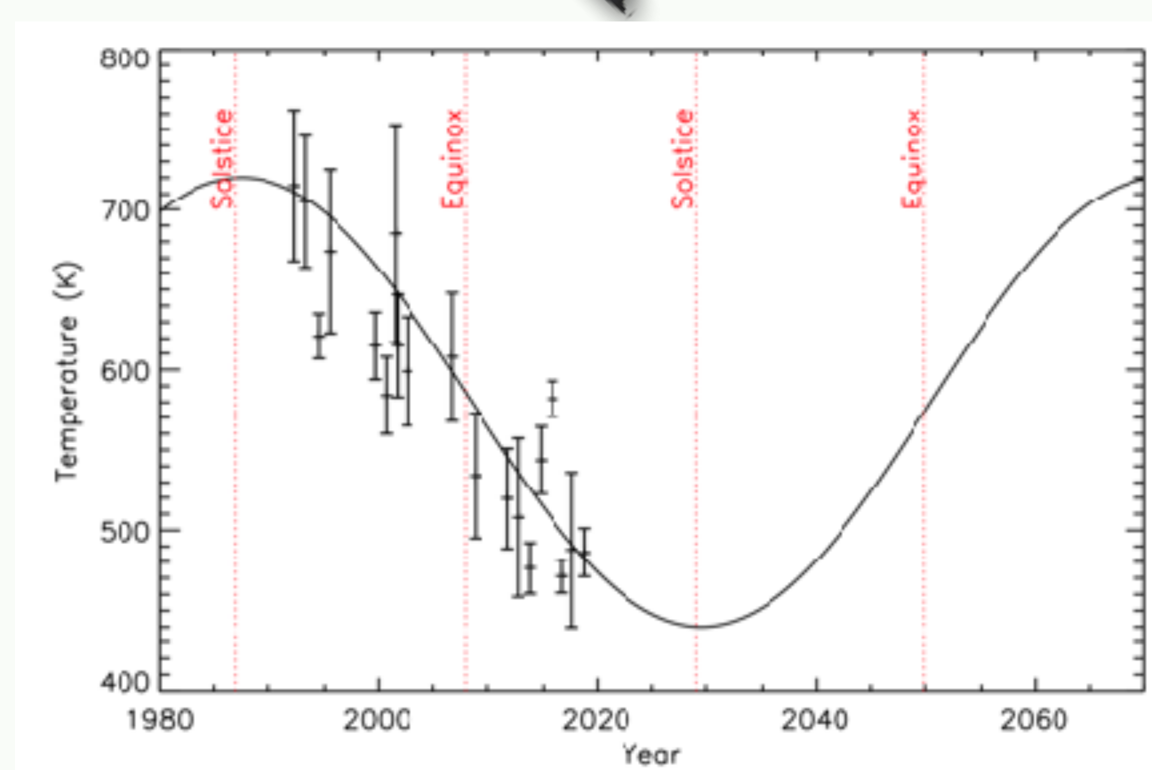


Magnetic Season



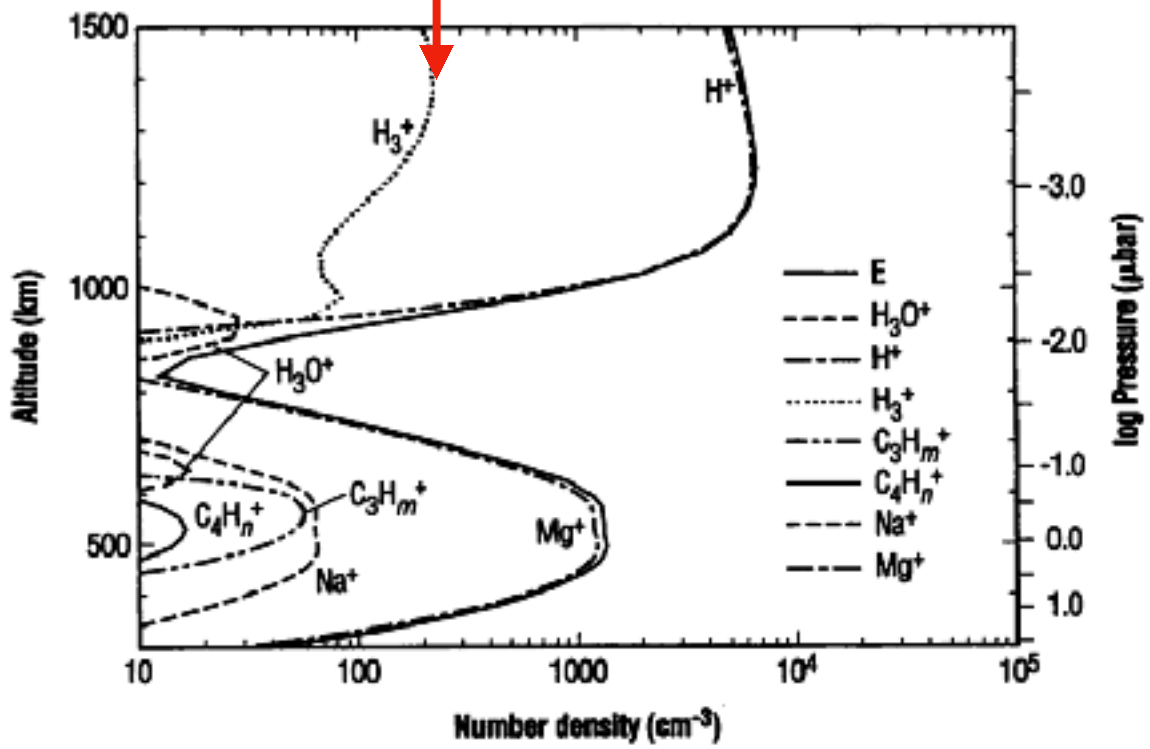
Melin et al. (2019, 2020)



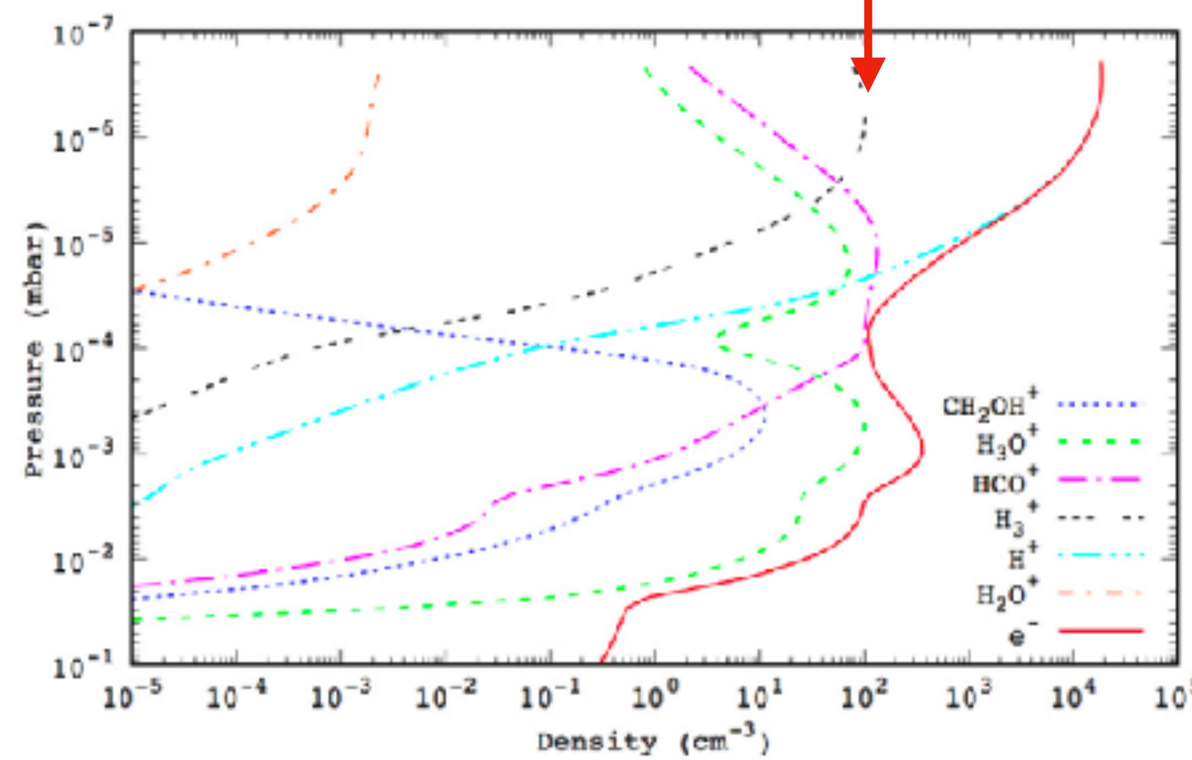


H_3^+ at Neptune

What do we expect to observe?



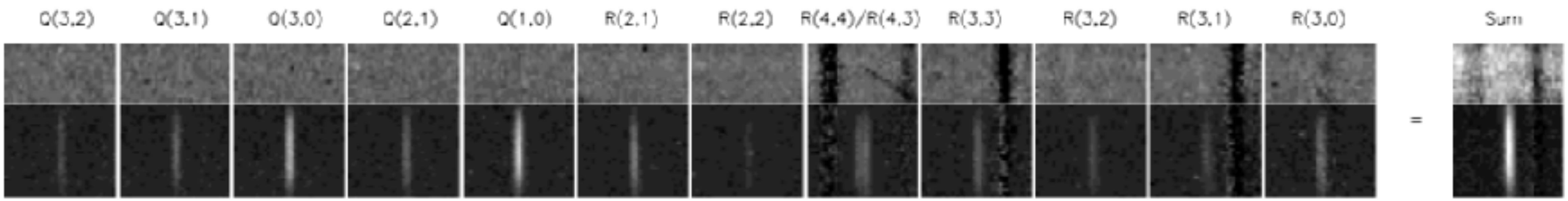
Lyons et al. (1995)



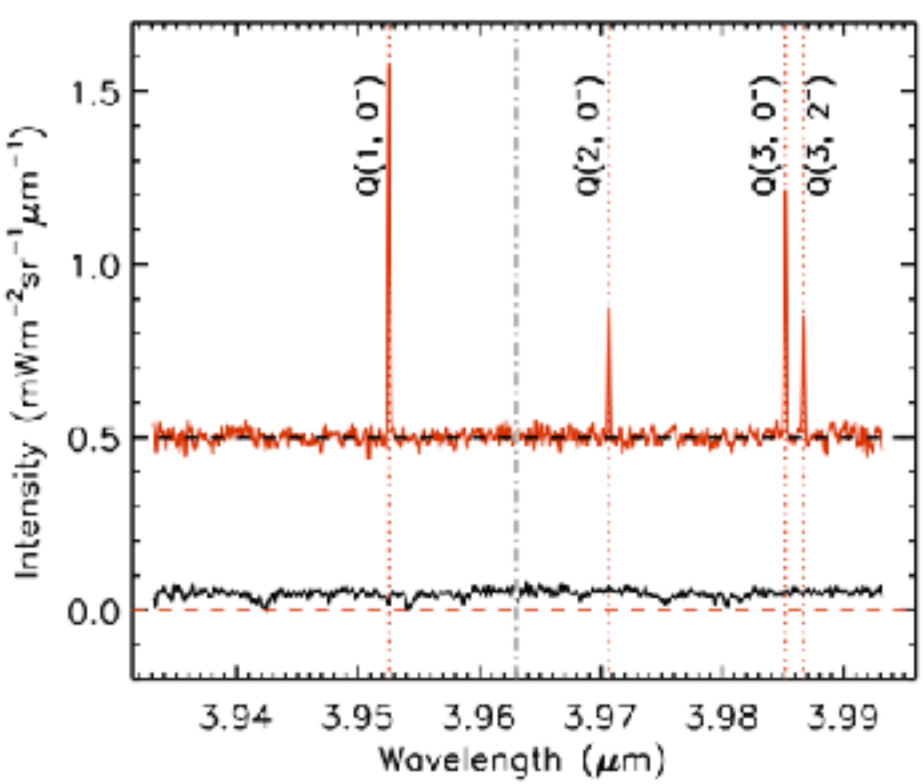
Dobrijevica et al. (2020)

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!?)

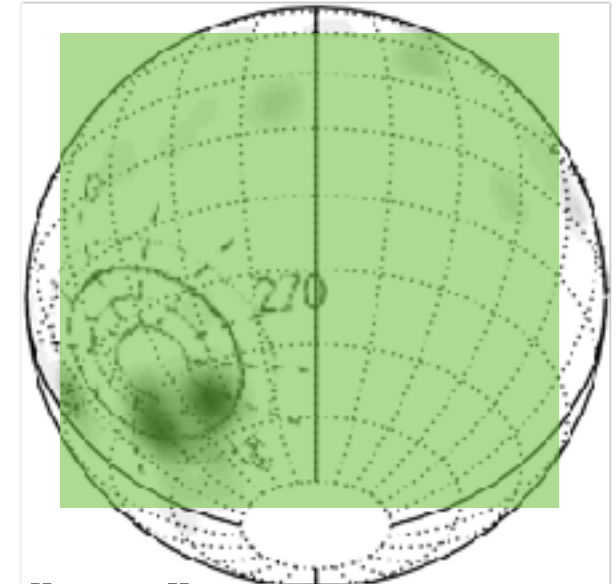
See Moore et al. (2020)

Pressing questions

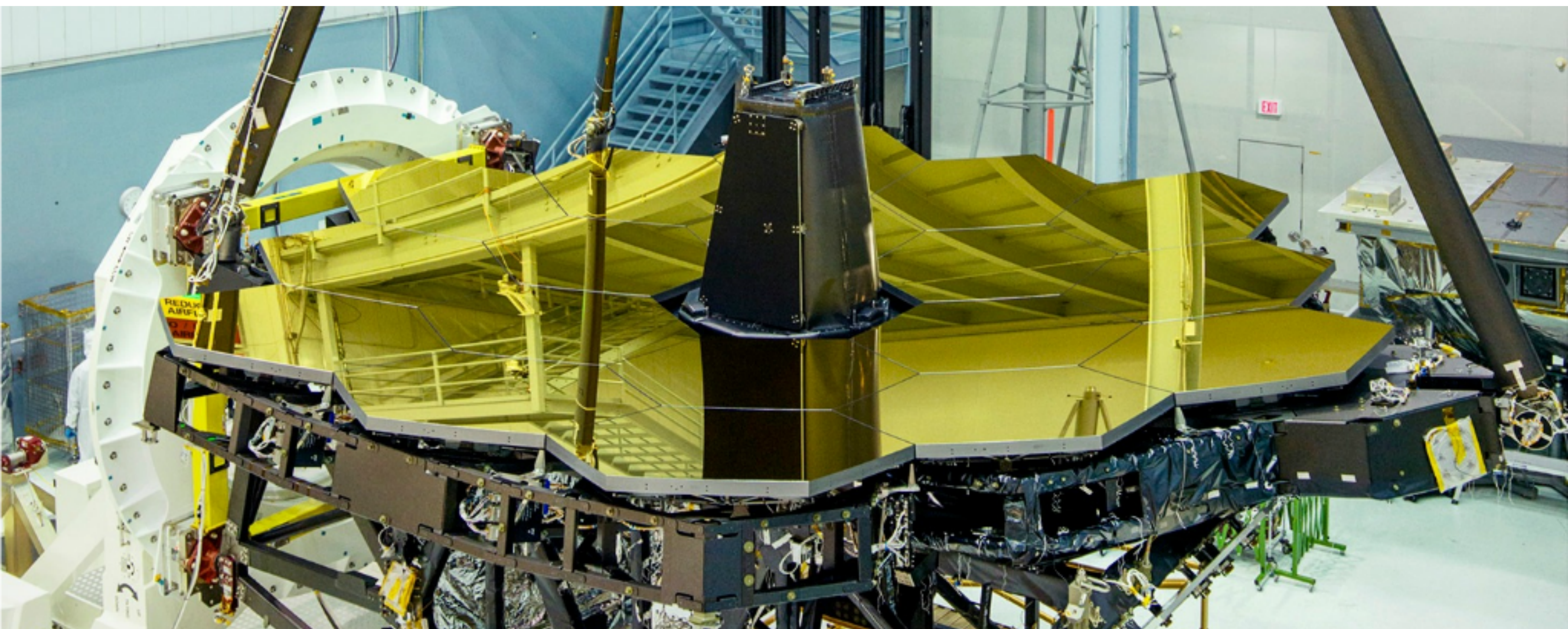
- The Energy Crisis remains - what drives this heating? Is it unique to the giant planets in our solar system?
- Why are the upper atmospheres of Uranus and Neptune so very different? The upper atmosphere of the giant planets are all very different.
- What is the nature of the interaction between the 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

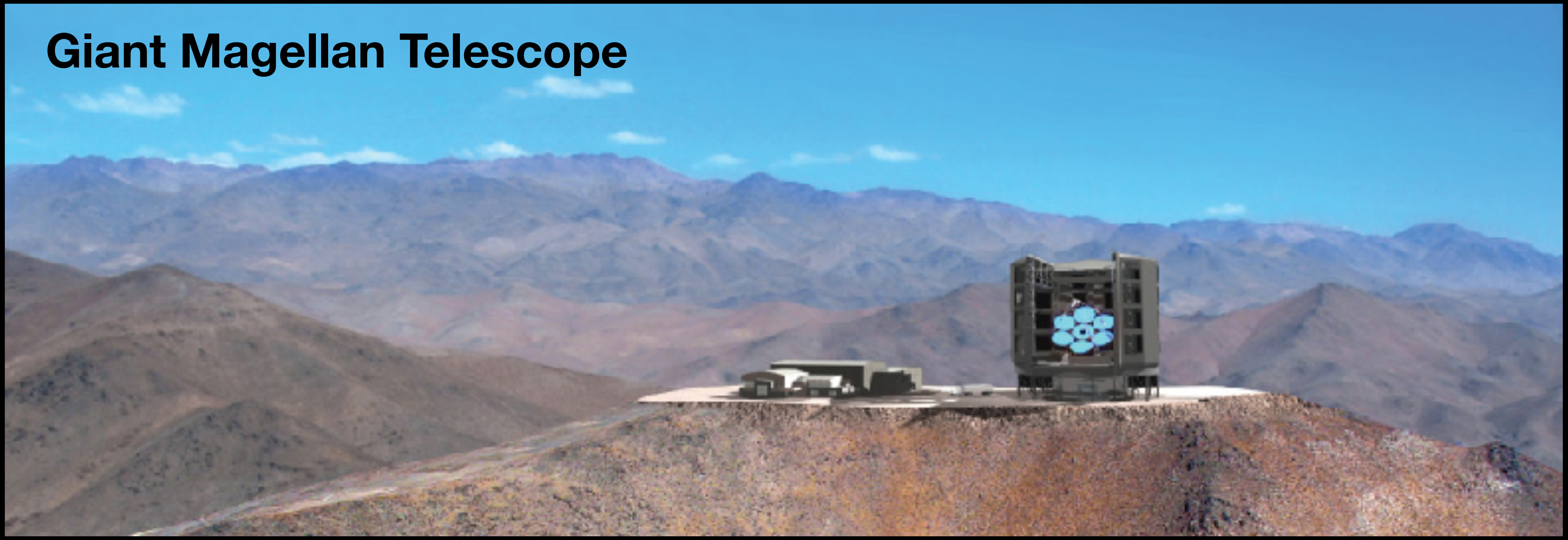
- Launch in Nov 2021?
- High sensitivity and spatial resolution, medium spectral resolution
- NIRSPEC instrument offers 3" x 3" FOV - perfect for Uranus - global mapping of H_3^+
- Uranus NIRSPEC and MIRI observations are in the Guaranteed Time Observing (GTO) programme



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!