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Solar Wind Power Likely Governs Uranus' Thermosphere Temperature

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Key Points:

- Ground-based telescopes have shown that Uranus' thermosphere steadily and dramatically cooled from ~1992 to ~2018
- We explain this cooling as due to declining solar wind kinetic power incident on Uranus' magnetosphere controlling thermosphere temperature
- Uranus' thermosphere appears to be governed by the solar wind, total auroral power may have also declined over the same period

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Abstract Observations of Uranus in the near-infrared by ground-based telescopes from 1992 to 2018 have shown that the planet's upper atmosphere (thermosphere) steadily cooled from ~700 to ~450 K. We explain this cooling as due to the concurrent decline in the power of the solar wind incident on Uranus' magnetic field, which has dropped by ~50% over the same period due to solar activity trends longer than the 11-year solar cycle. Uranus' thermosphere appears to be more strongly governed by the solar wind than any other planet where we have assessed this coupling so far. Uranus' total auroral power may also have declined, in contrast with the power of the radio aurora that we expect has been predominantly modulated by the solar cycle. In the absence of strong local driving, planets with sufficiently large magnetospheres may also have thermospheres predominantly governed by the stellar wind, rather than stellar radiation.

Plain Language Summary So far, we have only explored the Uranus planetary system with the *Voyager* 2 spacecraft, which flew past in 1986. This encounter led to many discoveries, and as many mysteries. One of these mysteries has only become clear since the flyby, as ground-based telescopes have been monitoring the temperature of Uranus' tenuous upper atmosphere and have found that this layer has been getting colder and colder since the *Voyager* era, unlike the deeper atmosphere that has stayed about the same temperature. By 2018 the temperature of this upper layer had almost halved, and neither the 11-year cycle of solar activity nor Uranus' changing seasons appear to have been in control. We finally provide a solution to this long-standing problem by identifying that the energy input to Uranus' magnetic field by the tenuous, high-speed flow of charged particles from the Sun has been similarly declining over decades. This interaction is what drives energy flow through space around the planet, and this energy ultimately does most of the heating of the upper atmosphere, where auroras are generated. We highlight that the situation may be similar at exoplanets with similarly large magnetospheres.

1. Introduction: Long-Term Cooling of Uranus' Thermosphere

Uranus' tenuous upper atmosphere (thermosphere) with its embedded ionized layer (ionosphere) separates the denser lower atmosphere from the magnetosphere space environment above (see the review by Melin (2020)). H_3^+ ions produced in this atmospheric layer quickly reach thermal equilibrium with the surrounding neutrals and emit photons in the near-infrared part of the spectrum (see the review by Miller et al. (2000)), allowing remote monitoring of Uranus' thermosphere temperature using ground-based telescopes (Encrenaz et al., 2003; Lam et al., 1997; Melin et al., 2011, 2013, 2019; Thomas et al., 2023; Trafton et al., 1993, 1999). Averages of a variable number of sporadic global temperature measurements in each year (hereafter referred to as typical annual temperatures) have revealed that Uranus' thermosphere steadily cooled from ~700 to ~450 K from 1992 to 2018 (Melin et al., 2019). Temperatures based on more recent measurements are yet to be reported. In contrast, there has been no clear long-term change in the temperature of the lower atmosphere (Orton, Fletcher, et al., 2014; Orton, Moses, et al., 2014; Orton et al., 2015).

The reason for this dramatic cooling of Uranus' thermosphere has been unclear. Uranus orbits the Sun at a distance that is ~19 times the mean Sun-Earth distance (an Astronomical Unit, au), and Uranus' obliquity of 97° produces extreme seasons over its 84-year orbit. In addition, we know that the thermosphere temperature has remained well above the value that would be produced by solar insolation alone (see the review by Melin (2020)), indicating that overall heating could be dominated by the coupling between the thermosphere and the magnetosphere via electric currents and precipitation of charged particles.

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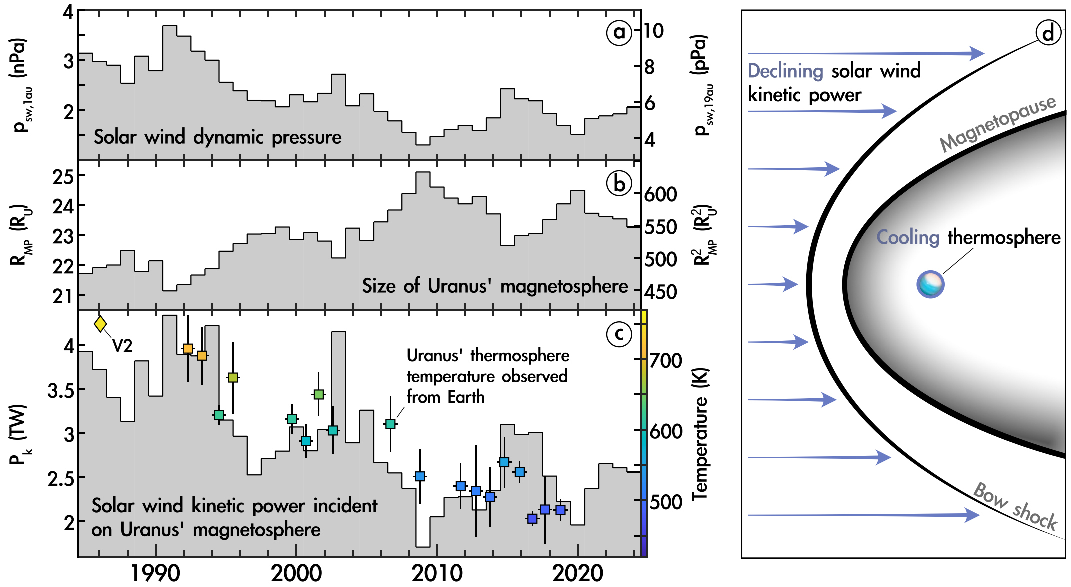

Figure 1. The long-term decline of both the solar wind kinetic power incident on Uranus' magnetosphere and the temperature of Uranus' thermosphere. (a) Annual-average solar wind dynamic pressure, p_{sw}, measured at Earth's orbit (1 au) and extrapolated to Uranus' orbit (19 au). (b) Calculated annual-average Uranus magnetopause standoff distance, R_{MP}, and the square of this distance as a measure of the size of the magnetosphere obstacle to the solar wind. (c) Calculated annual-average solar wind kinetic power incident on Uranus' magnetosphere, P_k, and comparison with typical annual thermosphere temperature. The diamond marker is the temperature derived from Voyager 2 ultraviolet occultations during the 1986 Uranus flyby, and the square markers are temperatures derived from ground-based near-infrared observations. (d) Diagram illustrating our solution to the Uranus thermosphere cooling problem.

An early idea to explain the cooling thermosphere was changing energy input from solar photons over the ∼11-year solar cycle (Trafton et al., 1993), now rejected because the cooling period spans ∼3 cycles. A solstice-to-equinox seasonal effect has also been rejected, since the cooling has continued since the 2007 equinox (Melin et al., 2013). Recent analysis of these ground-based near-infrared observations has gone beyond global-average temperatures to report how this temperature varies across a range of latitudes and longitudes (Thomas et al., 2023), eliminating explanations that invoke time-dependent viewing of a locally warmer region. At the time of writing, speculation the strong asymmetry in Uranus' magnetic field may lead to a solstice-to-solstice seasonal dependence of energy input from the magnetosphere is most prominent ("magnetic season") (Melin et al., 2013, 2019).

Here we introduce a new explanation focused on the concurrent decline in solar wind power that we suggest will ultimately provide closure to the Uranus thermosphere cooling problem, with implications beyond the Uranus system.

2. Observations: Long-Term Decline in Incident Solar Wind Power

Figure 1a shows the annual-average solar wind dynamic pressure, p_{sw}, from the OMNI database of spacecraft solar wind measurements at Earth's orbit (1 au). This kinetic energy density is by far the dominant source of solar wind energy at all the planets, almost equal to the total solar wind energy. The 1-yr averaging period spans more than 10 solar rotation periods of ∼27 days, allowing us to isolate and assess how the solar wind dynamic pressure has evolved over the decades during which Uranus' thermosphere has cooled. Modulation with the solar cycle (i.e., variation over a period of ∼11 years) is weak compared to the longer-term decline in annual-average pressure that began in ∼1990. This trend has been identified by the heliosphere science community (e.g., McComas et al., 2013), and it is well-established that the solar dynamo can vary significantly on timescales longer than decades. The solar wind dynamic pressure decline measured at Earth's orbit will have been reflected at Uranus' orbit, and we extrapolate to 19 au using an inverse-squared variation with heliocentric distance.

In Figure 1b we have used Uranus' dipole equator magnetic field strength, $B_0 = 2.25 \times 10^4$ nT (Herbert, 2009), and balanced Uranus' magnetic pressure with annual-average solar wind dynamic pressure at 19 au along the Uranus-Sun line to calculate Uranus' annual-average magnetopause standoff distance, defined as $R_{MP} = \left(\frac{2B_0^2}{k\mu_0 p_{sw}}\right)^{1/6}$, where $k = 0.881$ accounts for the processing of the flow from the upstream region to the subsolar point (Spreiter & Alksne, 1970) and μ_0 is the permeability of free space. Note that we have accounted for the strengthening of Uranus' magnetic field due to magnetopause currents by doubling the planetary magnetic field strength at the subsolar point. We give the standoff distance in units of Uranus radii (R_U; 1 = 25,559 km). The *Voyager* 2 inference of $R_{MP} = 18\ R_U$ at the time of its 1986 Uranus flyby is consistent with our annual-average value of $\sim$22 R_U in that year, as a recent re-assessment of the *Voyager* 2 solar wind measurements has shown that the encounter with Uranus' magnetosphere occurred during relatively high solar wind dynamic pressure (i.e., a more compressed magnetosphere than was typical at that time) (Jasinski et al., 2024). The long-term decline in solar wind dynamic pressure has caused gradual expansion of the typical size of Uranus' magnetosphere, and therefore also the cross-sectional area of Uranus' magnetosphere onto which the solar wind flow is incident, approximated as πR_{MP}^2.

Figure 1c shows our calculated annual-average solar wind kinetic power incident on Uranus' magnetosphere, $P_k = p_{sw} v_{sw} \pi R_{MP}^2$ (after Zarka et al. (2001)), where v_{sw} is the annual-average solar wind speed measured by spacecraft at 1 au (no scaling to Uranus' orbit required). From $\sim$1990 to $\sim$2020 this power has dropped by $\sim$50%, from $\sim$4 to $\sim$2 TW. Figure 1c also shows the typical annual temperature of Uranus' thermosphere for comparison. The diamond marker in early 1986 is the measurement of $\sim$750 K by *Voyager* 2 based on ultraviolet occultations of Uranus' atmosphere (Broadfoot et al., 1986), and the square markers are typical annual temperatures based on ground-based-telescope observations in the near-infrared (Melin et al., 2019). The *Voyager* 2 measurement may have been higher than the expected annual-average value that year because the flyby occurred during elevated solar wind dynamic pressure (Jasinski et al., 2024), and because *Voyager* 2 sampled the temperature at higher altitudes (in the exosphere) compared to the altitudes sampled by the later ground-based observations (below the exobase). The linear correlation between annual-average incident solar wind kinetic power and typical annual thermosphere temperature is quantified by a Pearson correlation coefficient of 0.7 ± 0.2, where the estimated coefficient uncertainty is based on approximate uncertainties of 10% and 30% in the two respective parameters (30% incident power uncertainty is based on the typical interquartile range of annual solar wind dynamic pressure distributions measured at 1 au).

3. Discussion

We propose that the concurrent, similar trend in the two independent data sets shown in Figure 1c is because there is a causal relationship between them that will resolve the Uranus thermosphere cooling problem, illustrated in Figure 1d. The *Voyager* 2 flyby in 1986 showed that Uranus' magnetosphere is Earth-like in the sense that it is also driven by the solar wind (see the review by Paty et al. (2020)). However, unlike Earth's thermosphere where solar insolation is the dominant heating mechanism, Uranus' magnetosphere presents an obstacle to the Sun that is $\sim$60 times larger than Earth's magnetosphere, promoting electrodynamic heating of Uranus' thermosphere due to the interaction with the solar wind that is needed at some level to explain all observed thermosphere temperatures (see the review by Melin (2020), note that both solar photon energy flux and solar wind kinetic energy flux have an inverse-squared variation with heliocentric distance). Declining solar wind kinetic power, or near-identically total solar wind power, should mean weakening heating of Uranus' thermosphere, leading to the observed long-term temperature decline.

This implies that Uranus' thermosphere is the most strongly powered by the solar wind that we have seen so far, given the almost 50% temperature reduction over recent decades. Establishing exactly how a fraction of the total incident solar wind energy heats Uranus' thermosphere is beyond the scope of this study, though a significant volume of research identifies the physics bridging this gap. For example, solar wind driving powers magnetospheric current systems that close in Uranus' ionosphere, where Joule heating is likely to be the primary heating mechanism. The energy transport from the solar wind to the atmosphere also powers auroral emissions in different wavelengths (see the reviews by Bhardwaj and Gladstone (2000) and Miller et al. (2005)).

Uranus' dynamic auroral emissions have been sporadically observed through a combination of ground-based telescopes, *Voyager* 2 flyby measurements, and the *Hubble Space Telescope* (see the review by Lamy (2020)).

Uranus' auroral emissions are also powered by the solar wind, so annual-average total auroral power may also have undergone a long-term decline with the incident solar wind power, possibly supported by the reports of shorter-term positive correlations between auroral brightness and solar wind dynamic pressure at the gas giants (e.g., Clarke et al., 2009). However, this depends on the accuracy of total auroral power as a diagnostic of thermosphere temperature, and we know that auroral power trends can differ between specific wavelength ranges. An example is the radio aurora, Uranian kilometric radiation (UKR) (e.g., Zarka, 1998). Measurements in the Solar System have demonstrated that auroral radio power scales with the incident magnetic power of the flow, instead of kinetic power (although magnetic and kinetic power can be closely correlated), where the relevant magnetic field component is perpendicular to the flow direction (Zarka et al., 2001). Measurements of the solar (interplanetary) magnetic field at 1 au indicate that over the period of thermosphere cooling the annual-average UKR power likely varied from order 10 to order 100 MW from solar minimum to solar maximum; that is, we do not expect UKR power underwent a similar long-term decline.

We predict that further reports of long-term changes in Uranus' thermosphere temperature will continue to track long-term changes in the incident solar wind kinetic power. On timescales shorter than a year, ground-based observations underlying the reported long-term temperature decline show that this global parameter can vary between individual observations that are separated by as little as approximately 1 day (Melin et al., 2019). We expect changes in incident power to also control this short-term temperature variability. Future assessments of this will require knowledge of the timescale for the global thermosphere temperature to respond to a change in the solar wind, consideration of other factors affecting the temperature on these timescales, as well as a careful analysis of how much we can deduce about short-term solar wind variability at Uranus around times of apparent opposition with Earth based on the outward propagation of measured solar wind conditions at 1 au (e.g., Zieger & Hansen, 2008). Monitoring of Uranus' thermosphere around such times by the *James Webb Space Telescope* would test our proposition and provide new insights into how the coupling between the solar wind and Uranus' atmosphere works. Significant progress in understanding this broad topic, and particularly how solar wind energy crosses the magnetopause boundary (e.g., Gershman & DiBraccio, 2024; Masters, 2018), must rely on future spacecraft exploration (e.g., Hofstadter et al., 2019).

Beyond Uranus, we know the thermosphere temperature at all the Solar System's giant planets is well above the value expected from solar insolation alone (see the review by Melin (2020)), also thought to be due to heating related to electrodynamic coupling to space and with different ideas about how heat is transported from the auroral regions to other latitudes (Müller-Wodarg et al., 2019; O'Donoghue et al., 2021). At Jupiter, this heating is dominated by processes occurring inside the magnetosphere related to Jupiter's fast rotation and the volcanic moon Io, so we do not think our Uranus proposition has direct implications for this system. However, at Saturn, investigating long-term global thermosphere temperature trends may help establish the relative importance of internal and external driving of the magnetosphere. The most direct solar-system implication of our Uranus proposition is that Neptune's thermosphere should have been cooling in qualitatively the same fashion, and for the same reason, since Neptune's magnetosphere also appears to be driven by the solar wind and the magnetospheric scale is similar (see the review by Paty et al. (2020)). This is consistent with the lack of previous ground-based detection of H_3^+ near-infrared emission from Neptune (Melin et al., 2017; Moore et al., 2020).

Beyond the solar system, this explanation for Uranus' thermosphere cooling implies that exoplanet companions to host stars without strong local driving (like at Jupiter) and with sufficiently large magnetospheres will undergo a predominantly electrodynamic interaction with their parent star in which the stellar wind, and not stellar radiation, most strongly governs the thermal evolution of the upper atmosphere, and possibly also the power of specific types of auroral emission. If our Uranus proposition holds, it would therefore suggest that existing models that neglect thermosphere energy input powered by the stellar wind (e.g., Miller et al., 2000; Koskinen et al., 2010; Yelle, 2004) may underestimate H_3^+ emissions from some exoplanets.

At present, the search for H_3^+ emissions from exoplanet systems largely focuses on hot Jupiters experiencing strong extreme ultraviolet (EUV) irradiation by their host stars (e.g., Brittain & Rettig, 2002; Goto et al., 2005; Laughlin et al., 2008; Lenz et al., 2016; Shkolnik et al., 2006), yet to yield any confirmed detections. High stellar wind pressures around these close-in exoplanets and the possibility that these conditions may permanently suppress exoplanet magnetic field strengths (e.g., Heyner et al., 2011) appear to reduce the likelihood of large hot-Jupiter magnetospheres, also reducing the likelihood that H_3^+ emissions from the exoplanets are underestimated.

We suggest such searches could benefit from also selecting exoplanets that are further from their host stars. Warm Jupiters may be more likely than hot Jupiters to possess large magnetospheres, which our Uranus proposition suggests would then lead to currently underestimated H_3^+ emissions. Searches may also benefit from selecting exoplanets around host stars with strong stellar winds, rather than high EUV flux. In closing, we caution against making H_3^+ emission predictions based on Jupiter, where the electrodynamic interaction is dominated by the presence of active moons.

Data Availability Statement

Annual-average solar wind parameters at Earth's orbit are publicly available in the OMNI database, obtained from the GSFC/SPDF OMNIWeb interface at https://omniweb.gsfc.nasa.gov. Typical annual global temperatures of Uranus' thermosphere are listed in Table 3 of Melin et al. (2019). Derived data shown in Figure 1 is available in the Zenodo data repository (Masters et al., 2024).

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