

The bolometric Bond albedo and energy balance of Uranus

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Accepted 2025 May 13. Received 2025 April 28; in original form 2025 February 26

ABSTRACT

Using a newly developed ‘holistic’ atmospheric model of the aerosol structure in Uranus’s atmosphere, based upon observations made by *Hubble Space Telescope* (HST)/Space Telescope Imaging Spectrograph (STIS), Gemini/Near-Infrared Integral Field Spectrometer (NIFS), and NASA Infrared Telescope Facility (IRTF)/SpeX from 2000 to 2009, we make a new estimate of the bolometric Bond albedo of Uranus during this time of $A^* = 0.338 \pm 0.011$, with a phase integral of $q^* = 1.36 \pm 0.03$. Then, using a simple seasonal model, developed to be consistent with the disc-integrated blue and green magnitude data from the Lowell Observatory from 1950 to 2016, we model how Uranus’s reflectivity and heat budget vary during its orbit and determine new orbital-mean average values for the bolometric Bond albedo of $\overline{A^*} = 0.349 \pm 0.016$ and for the absorbed solar flux of $\overline{P_{in}} = 0.604 \pm 0.027 \text{ W m}^{-2}$. Assuming the outgoing thermal flux to be $\overline{P_{out}} = 0.693 \pm 0.013 \text{ W m}^{-2}$, as previously determined from Voyager 2 observations, we arrive at a new estimate of Uranus’s average heat flux budget of $P_{out}/P_{in} = 1.15 \pm 0.06$, finding considerable variation with time due to Uranus’s significant orbital eccentricity of 0.046. This leads the flux budget to vary from $P_{out}/P_{in} = 1.03$ near perihelion, to 1.24 near aphelion. We conclude that although P_{out}/P_{in} is considerably smaller than for the other giant planets, Uranus is not in thermal equilibrium with the Sun.

Key words: radiative transfer – scattering – techniques: photometric – planets and satellites: atmospheres.

1 INTRODUCTION

All the Solar system giant planets appear to emit more thermal radiation to space than they absorb from the Sun, indicating that they have substantial reservoirs of internal heat left over from formation. For planets in thermal equilibrium with the Sun the ratio of the total power thermally emitted to the total solar power absorbed, i.e. P_{out}/P_{in} , would be equal to 1.0, but generally accepted estimates of this ratio for the giant planets, based on observations made by the NASA Voyager missions, are Jupiter: 1.67 ± 0.09 (Hanel et al. 1981), Saturn: 1.78 ± 0.09 (Hanel et al. 1983), Uranus: 1.06 ± 0.08 (Pearl et al. 1990), and Neptune: 2.61 ± 0.28 (Pearl & Conrath 1991), although the values for Jupiter and Saturn have recently been updated from Cassini observations to 2.132 ± 0.051 (Li et al. 2018) and 2.39 ± 0.21 (Wang et al. 2024), respectively. The flux ratio seems to be particularly low for Uranus and is consistent with Uranus being in thermal equilibrium with the Sun, which would make it a very notable outlier from the rest of the giant planets.

The low level of the P_{out}/P_{in} ratio for Uranus, combined with its very high obliquity (i.e. inclination of its spin axis relative to its orbital plane) of 97° led Stevenson (1986) to suggest that towards the end of its initial formation Uranus suffered an oblique impact with a large planetesimal (of approximately 2 Earth masses) that

tipped Uranus’s spin axis over on its side, heated just the outer shell of the planet, which has since cooled, and threw off of a disc of material, which has since coalesced to form a regular, compact satellite system. Stevenson (1986) argued that Neptune, in contrast, may have suffered a more head-on collision that created high internal temperatures and did not throw off a disc of material, which could explain Neptune’s high observed P_{out}/P_{in} ratio and absence of a compact satellite system. This hypothesis has been returned to a number of times since, most recently by Reinhardt et al. (2020), who performed smoothed particle hydrodynamics (SPH) simulations that support this scenario. Alternatively, it has been proposed that compositional gradients deep in Uranus’s atmosphere may give rise to a deep thermal boundary layer, inhibiting convection and trapping heat (Nettelmann et al. 2016; Vazan & Helled 2020; Scheibe, Nettelmann & Redmer 2021), thus reducing P_{out} . Another possibility is that since existing observations of Uranus cover only a fraction of a Uranian year, they may have been made during a quiescent meteorological period when heat release was low. In Saturn’s atmosphere, for example, increased storm activity was found to affect the planet’s heat budget by modifying both the amount of regional emitted heat and absorbed solar energy (Li & Ingersoll 2015). Increased storm activity at Uranus could result in changes in heat release by varying the atmosphere’s reflectivity and therefore the amount of absorbed sunlight (e.g. Fletcher et al. 2020), and also the degree of vertical heat transport via cumulus convection driven by the condensation of species such as CH_4 , H_2O , NH_4SH , NH_3 , and/or H_2S (Sromovsky & Fry 2005; Hueso, Guillot & Sánchez-Lavega 2020).

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Table 1. Determinations of albedo and energy balance of Uranus (extended from table 1 of Pearl et al. 1990).

Reference	Year	p	q	A	T_{eff}	$P_{\text{out}}/P_{\text{in}}$
Lockwood et al. (1983)(from Younkin 1970)	1962	0.228 ± 0.008	$1.50^{+0.14}_{-0.17}$	0.342 ± 0.041	$57.0 \pm 2.5^{\text{a}}$	0.92 ± 0.17
Lockwood et al. (1983)	1981	0.262 ± 0.008	$1.50^{+0.14}_{-0.17}$	0.393 ± 0.041	$57.0 \pm 2.5^{\text{a}}$	1.00 ± 0.19
Neff et al. (1985)	1981	0.28 ± 0.02	1.2	0.34 ± 0.02	$58.6 \pm 2.0^{\text{b}}$	1.12 ± 0.22
Pollack et al. (1986)	1982–1985	0.270 ± 0.020	1.26 ± 0.11	0.343 ± 0.055	$57.7 \pm 2.0^{\text{c}}$	1.10 ± 0.22
Pollack et al. (1986)	orbital mean	0.253 ± 0.046	1.26 ± 0.11	0.319 ± 0.051	$57.7 \pm 2.0^{\text{c}}$	1.06 ± 0.21
Pearl et al. (1990)	1986	0.231 ± 0.048	1.40 ± 0.14	0.322 ± 0.049	59.1 ± 0.3	1.14 ± 0.09
Pearl et al. (1990)	orbital mean	0.215 ± 0.046	1.40 ± 0.14	0.300 ± 0.049	59.1 ± 0.3	1.06 ± 0.08
This investigation	2000–2009	0.249 ± 0.007	1.36 ± 0.03	0.338 ± 0.011	59.1 ± 0.3	1.24 ± 0.06
This investigation	orbital mean	0.257 ± 0.007	1.36 ± 0.03	0.349 ± 0.016	59.1 ± 0.3	1.15 ± 0.06

Note. ^a Courtin et al. (1979), ^bHildebrand et al. (1985), ^cOrton (1985).

Finally, there remains the possibility that the Voyager measurement of Uranus’s outgoing thermal flux may be underestimated due to calibration uncertainties (e.g. Li et al. 2018). However, all these conclusions and interpretations are contingent upon the accuracy of the $P_{\text{out}}/P_{\text{in}}$ estimates, and it can be seen that for Uranus this ratio is only currently constrained to lie in rather a broad range from 0.98 to 1.14.

In this paper, we use the ‘holistic’ aerosol model of Uranus and Neptune, developed by Irwin et al. (2022) and based upon observations made by *HST*¹/*STIS*², Gemini/*NIFS*³ and *IRTF*⁴/*SpeX* from 2000 to 2009 to improve upon the $P_{\text{out}}/P_{\text{in}}$ estimate for Uranus. We first determine the bolometric Bond albedo and $P_{\text{out}}/P_{\text{in}}$ flux ratio of Uranus in the early 2000s and then use a simple seasonal model, developed by Irwin et al. (2024) and consistent with the disc-integrated blue and green magnitude data from the Lowell Observatory (Lockwood 2019), to model how Uranus’s reflectivity and heat budget vary during Uranus’s year.

2 MEASUREMENTS OF THE BOND ALBEDO AND POWER BALANCE OF URANUS

At a particular wavelength the geometric albedo of a planet, p , is defined as the power of the reflected sunlight at a phase angle of 0° compared with that from a flat, perfectly reflecting Lambertian surface of the same cross-sectional area. The Bond albedo A , however, is the total fraction of sunlight incident on the planet that is reflected away in **all** directions and is related to the geometric albedo, p , by the relation

$$A = pq, \quad (1)$$

where q is the *phase integral*, defined as the integral of the flux $I(\alpha)$ scattered from the planet into phase angle α :

$$q = 2 \int_0^\pi \frac{I(\alpha)}{I(0)} \sin \alpha d\alpha. \quad (2)$$

If we integrate the incident and reflected powers over all wavelengths, then we arrive at ‘integrated’ or ‘bolometric’ values of these parameters, which we denote as: p^* , q^* , and A^* .

The Bond albedo and radiative heat balance of Uranus has been addressed by a number of studies. Lockwood et al. (1983) analysed high-resolution spectrophotometry observations of Uranus made in 1981 at the Lowell Observatory and found $p^* = 0.262 \pm 0.008$,

$q^* = 1.50^{+0.14}_{-0.17}$, and $A^* = 0.393 \pm 0.041$. It was also found that the albedo had risen significantly since previous observations made between 1961 and 1963 (Younkin 1970), for which the following values were computed: $p^* = 0.228 \pm 0.008$ and $A^* = 0.342 \pm 0.041$. Using $A^* = 0.393 \pm 0.041$ the estimated absorbed solar power per unit area over the whole planet in 1981 was estimated to be $0.563\text{--}0.643 \text{ W m}^{-2}$, while assuming the effective blackbody temperature of Uranus in the infrared to be $T_{\text{eff}} = 57.0 \pm 2.5 \text{ K}$ (Courtin et al. 1979), the outgoing flux was estimated to be $0.500\text{--}0.711 \text{ W m}^{-2}$. Hence, Lockwood et al. (1983) estimated the internal heat flux to be $< 0.122 \text{ W m}^{-2}$. From these results (summarized in Table 1), we here derive an estimate (adding errors in quadrature) of $P_{\text{out}}/P_{\text{in}} = 1.00 \pm 0.19$. For the 1961–1963 data, we estimate from these data that $P_{\text{out}}/P_{\text{in}} = 0.92 \pm 0.17$.

Neff et al. (1985) analysed high-resolution spectrophotometry observations of Titan, Uranus, and Neptune made in around 1981 by the International Ultraviolet Explorer (Caldwell et al. 1981), Macdonald Observatory (Neff et al. 1984), and *IRTF*, and estimated $p^* = 0.28 \pm 0.02$, $q^* = 1.2$, and $A^* = 0.34 \pm 0.02$. The absorbed solar flux was estimated to be the same as that emitted from a blackbody of temperature $T = 57.0 \pm 2.0 \text{ K}$. Assuming the effective blackbody temperature of Uranus in the infrared to be $T_{\text{eff}} = 58.6 \pm 2.0 \text{ K}$ (Hildebrand et al. 1985), the internal luminosity of Uranus was estimated to be $L_{\text{int}} = (0.6 \pm 1.4) \times 10^{15} \text{ W}$. From these results we estimate the internal heat flux (using their assumed Uranus radius of $25\,250 \text{ km}$) to be $\leq 0.25 \text{ W m}^{-2}$, and from this we here derive an estimate (adding errors in quadrature) of $P_{\text{out}}/P_{\text{in}} = 1.12 \pm 0.22$ (Table 1).

Pollack et al. (1986) constructed an atmospheric aerosol model that was consistent with phase angle observations ($0 - 85^\circ$) from ground-based observatories (Neff et al. 1984) and *Voyager-1/ISS*⁵ observations made between 1982 and 1985. From this model, Pollack et al. (1986) calculated that during this period, $p^* = 0.27 \pm 0.02$, $q^* = 1.26 \pm 0.11$, and $A^* = 0.343 \pm 0.055$. Since Lockwood et al. (1983) noted a 14 per cent increase in Uranus’s albedo from 1961–1963 to 1981, Pollack et al. (1986) assumed that the orbitally averaged values of their albedos should be reduced by 7 per cent to $\overline{p^*} = 0.253 \pm 0.046$, and $\overline{A^*} = 0.319 \pm 0.051$. The orbitally averaged absorbed solar flux was estimated to be the same as the flux emitted from a blackbody of temperature $T = 56.9 \pm 2.0 \text{ K}$. Assuming the effective blackbody temperature of Uranus in the infrared to be $T_{\text{eff}} = 57.7 \pm 2.0 \text{ K}$ (Orton 1985), Pollack et al. (1986) concluded that the internal heat flux was $\leq 0.27 \text{ W m}^{-2}$. From these results, we here derive an estimate of $P_{\text{out}}/P_{\text{in}} = 1.06 \pm 0.21$ (Table 1). We

¹*HST* – Hubble Space Telescope.

²*STIS* – Space Telescope Imaging Spectrograph

³*NIFS* – Near-Infrared Integral Field Spectrometer

⁴*IRTF* – NASA Infrared Telescope Facility.

⁵*ISS* – Imaging Subsystem

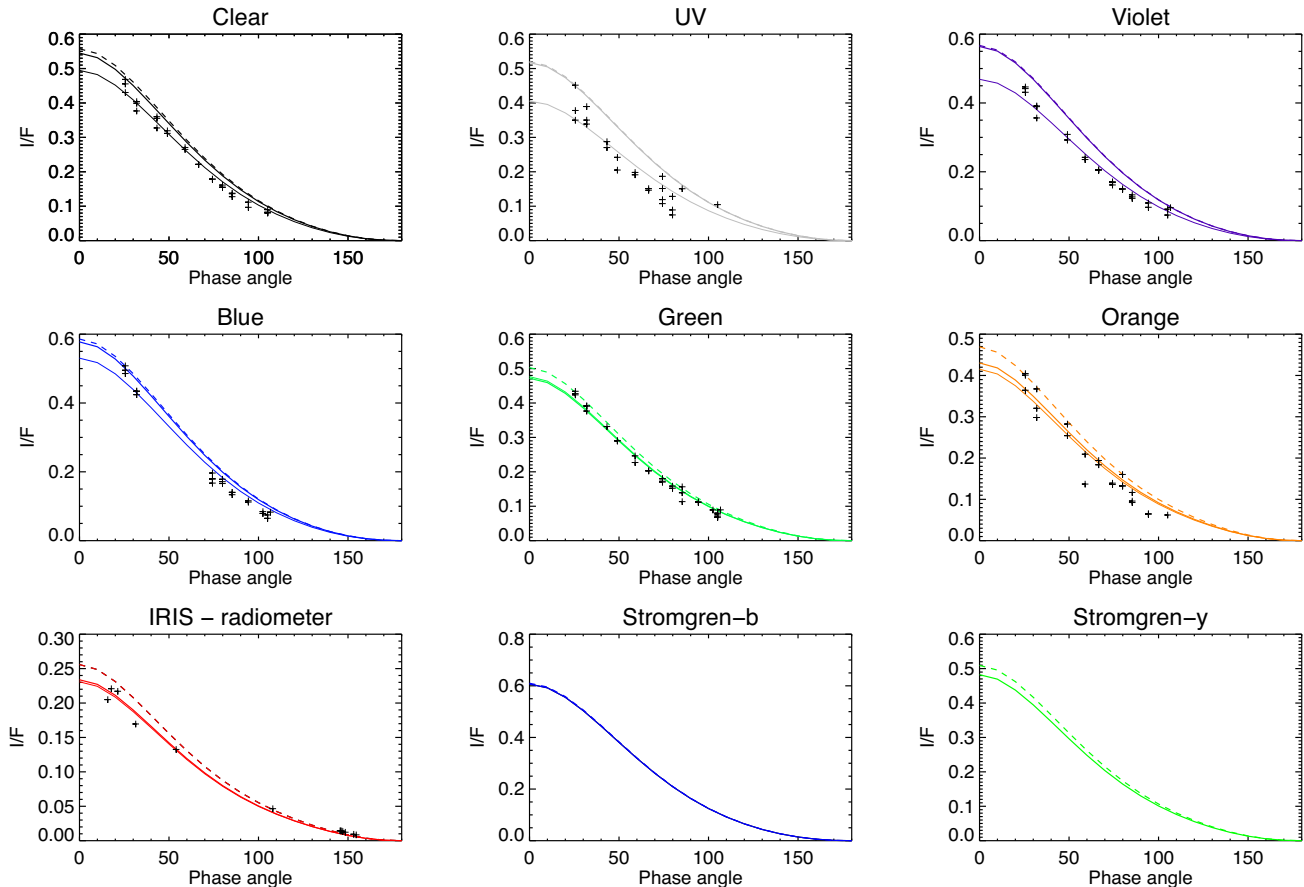


Figure 1. Phase curves calculated from our NEMESIS simulations of Uranus and averaged over different filter profiles of Voyager/ISS, Voyager/IRIS, and for reference, Strömgren-*b* and Strömgren-*y*. The Voyager phase curve simulations are compared with the ISS observations processed by Wenkert et al. (2023) and IRIS observations processed by Pearl et al. (1990). Here, the solid lines show the calculations from our model atmosphere fitted to observations between 2000 and 2009, while the dashed lines show calculations that have been corrected to the time of the Voyager-2 observations in 1986, when Uranus was more reflective, using the seasonal albedo curves shown later in Fig. 4. The thin lines are the simulated curves scaled to match the observations most closely, showing the excellent modelling of the shape of these curves, if not necessarily the exact photometric calibration for each filter.

have here also scaled this value (using the Bond albedo estimates) to an equivalent flux ratio in 1982–1985 of $P_{\text{out}}/P_{\text{in}} = 1.10 \pm 0.22$.

Pearl et al. (1990) used Voyager/IRIS⁶ radiometer observations of Uranus made during the Voyager 2 flyby of Uranus in January 1986 to estimate Uranus’s Bond albedo. Measurements of the reflectivity of Uranus, integrated over the IRIS radiometer, were made at several phase angles and are shown in Fig. 1 and compared with the Voyager-1/ISS phase angle observations used by Pollack et al. (1986), and more recently extended by Wenkert et al. (2023). The IRIS radiometer is sensitive from 0.3 to 1.9 μm and the IRIS radiometer sensitivity function is compared with the Voyager/ISS filter functions and a reference Uranus spectrum in Fig. 2. Pearl et al. (1990) assumed that the IRIS-radiometer-averaged reflectivities were equivalent with the bolometric values and thus reported $p^* = 0.231 \pm 0.048$, $q^* = 1.4 \pm 0.14$, and $A^* = 0.322 \pm 0.049$. These observations were made in 1986 near Uranus’s solstice, when Uranus is at its brightest. Pearl et al. (1990) noted that their albedoes were thus likely to be greater than the average value and so revised their Bond albedo figure down by 7 per cent (from Lockwood et al. 1983) to arrive at an estimate of the orbital mean Bond albedo of $A^* = 0.300 \pm 0.049$. By analysing the IRIS infrared spectrometer data (covering ~ 11 to 55 μm) and extending to longer wavelengths with modelling, Pearl

et al. (1990) then estimated that the overall infrared flux emitted into all directions to be $F = 0.693 \pm 0.013 \text{ W m}^{-2}$, equivalent to a blackbody of temperature of $T = 59.1 \pm 0.3 \text{ K}$, which is larger than all the other equivalent blackbody temperatures assumed in the previous studies discussed here. Using these numbers Pearl et al. (1990) concluded that $P_{\text{out}}/P_{\text{in}} = 1.06 \pm 0.08$. We have here also scaled this (from the Bond albedoes) to an equivalent flux ratio in 1986 of $P_{\text{out}}/P_{\text{in}} = 1.14 \pm 0.09$.

The comparison of these estimates for Uranus’s albedo and radiative heat balance from these studies is summarized in Table 1.

3 SIMULATING THE BOND ALBEDO OF URANUS

In this study, we simulate the reflectivity spectrum of Uranus using our NEMESIS (Non-linear optimal Estimator for MultivariatE spectral analysis, Irwin et al. 2008) radiative transfer and retrieval model. NEMESIS uses the plane-parallel doubling and adding multiple scattering scheme of Plass, Kattawar & Catchings (1973) and has been used in several radiative transfer studies of Uranus and Neptune. Using NEMESIS, Irwin et al. (2022) recently developed an ‘holistic’ aerosol model for Uranus and Neptune, which was simultaneously consistent with *HST*/STIS spectral imaging observations from 0.30–1.02 μm , Gemini/NIFS spectral imaging observations from 1.4 to 1.8

⁶IRIS – Infrared Interferometer Spectrometer

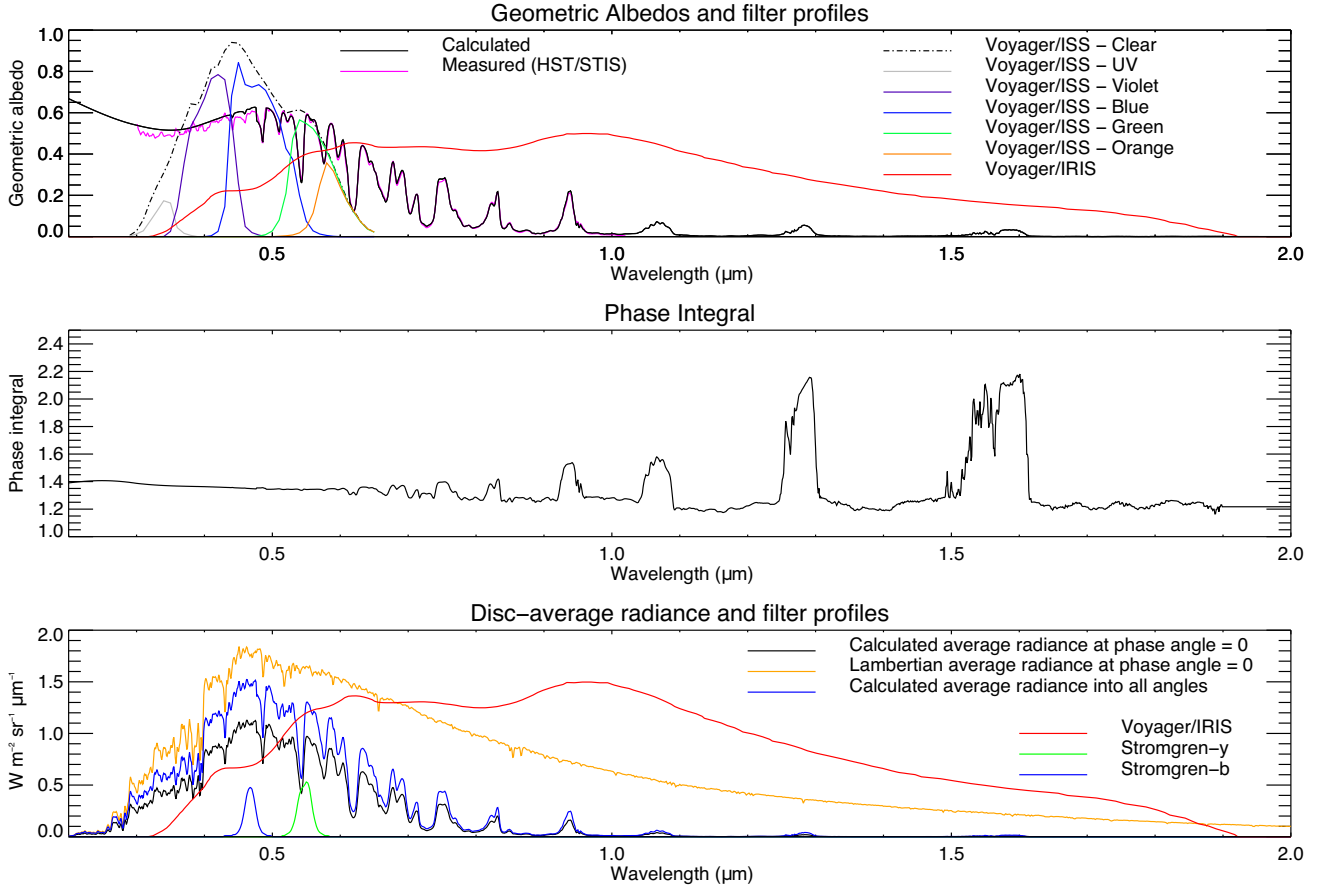


Figure 2. Simulated and measured spectra of Uranus. Top plot compares the simulated geometric albedo spectrum compared with the Voyager/ISS filter functions (Danielson et al. 1981) and the Voyager/IRIS radiometer response function (Hanel et al. 1981). In addition, we show the measured *HST/STIS* albedo spectrum of Karkoschka & Tomasko (2009), showing that our model agrees well with the geometric albedo spectrum measured in 2002 by *HST/STIS*, as expected. Middle panel shows our calculated phase integral spectrum $q(\lambda)$ from these calculations. Bottom plot compares the modelled disc-averaged radiance spectrum (calculated at phase angle $\alpha = 0^\circ$) with the expected radiance from a perfectly scattering Lambertian surface. In addition, we show the disc-averaged reflectance into all angles and compare this with the Strömgren-*b* and Strömgren-*y*, and Voyager/IRIS radiometer filter functions.

μ m, and a central meridian line-averaged IRTF/SpeX observation from 0.8 to 1.9 μ m. For Uranus, the *HST/STIS* observations were made in 2002 (Karkoschka & Tomasko 2009), the Gemini/NIFS observations were made in 2009 (Irwin et al. 2011), and the IRTF/SpeX observation was made in 2000 (Rayner, Cushing & Vacca 2009). This model consisted of a vertically extended semi-infinite deep cloud deck ‘Aerosol-1’, a vertically thin middle ‘Aerosol-2’ layer, centred at 1–2 bar, coincident with the methane condensation level, and a vertically extended upper-tropospheric ‘Aerosol-3’ haze at pressures less than 1.5 bar. By adjusting the cloud opacities, particle sizes, complex refractive index spectra of these three layers and also varying the pressure of the Aerosol-2 layer, the model was able to reproduce the observed reflectivity and limb-darkening curves of both Uranus and Neptune, where the limb-darkening was found to be consistent with the model of Minnaert (1941):

$$(I/F) = (I/F)_0 \mu_0^k \mu^{k-1}. \quad (3)$$

Here, μ is the cosine of the viewing zenith angle, μ_0 is the cosine of the solar zenith angle, and the fitted parameters are the nadir reflectances $(I/F)_0$ and the limb-darkening coefficients k .

This holistic model has since been slightly revised by James et al. (2023) and Irwin et al. (2024), with the semi-infinite Aerosol-1

component replaced by a vertically thin cloud deck centred at ~ 5 bar. This revised model was found to fit the observations just as well, but made it easier to disentangle the spectral effects of the Aerosol-1 and Aerosol-2 layers, leading to more reliable and robust retrievals.

The disc-integrated magnitude of Uranus at Strömgren-*y* and -*b* wavelengths was measured nearly annually from 1950 to 2016 by observers at the Lowell Observatory (Lockwood 2019), who compiled a unique record of the seasonal variation of Uranus’s brightness and colour. Irwin et al. (2024) converted these magnitude data to disc-averaged reflectivities and compared these with *HST/WFC3*⁷ observations from 2014 to 2022, and *HST/STIS* observations made in 2002, 2012, and 2015 (Karkoschka & Tomasko 2009; Sromovsky et al. 2014, 2019), finding very good photometric agreement between all three data sets. Irwin et al. (2024) then used the revised holistic model to simulate the seasonal variation in Uranus’s albedo at Strömgren-*y* and -*b* wavelengths.

Taking our best modified holistic model fit to the Uranus data of Irwin et al. (2022) we computed the mean reflectivity spectrum of Uranus’s atmosphere from 0.2 to 1.9 μ m at all possible solar and

⁷WFC3 – Wide Field Camera 3

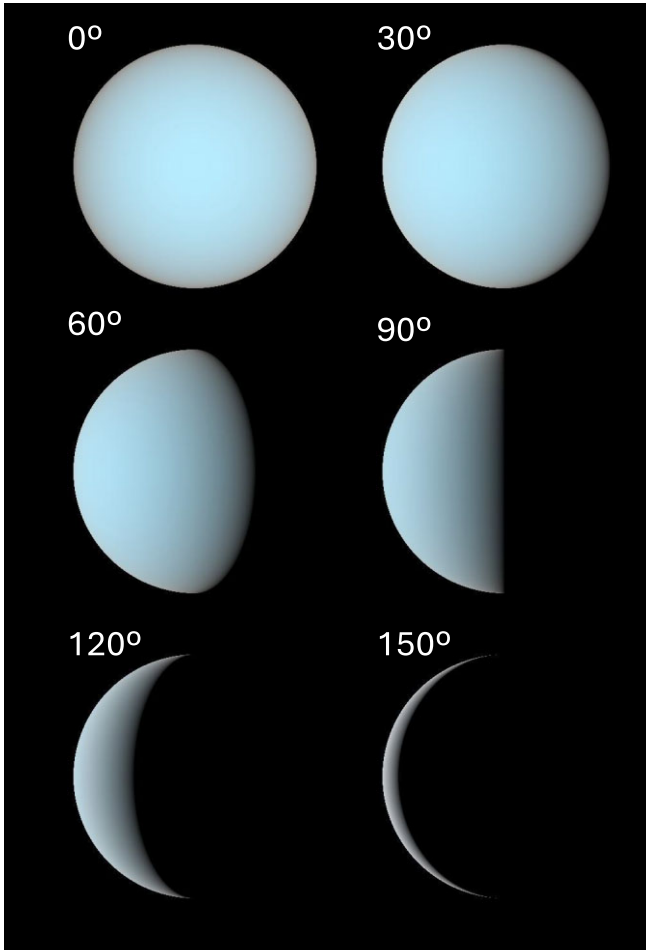


Figure 3. Computed ‘true-colour’ appearance of Uranus calculated with our NEMESIS radiative transfer code at six different representative phase angles. Following the procedure of Irwin et al. (2024), the computed spectra in each pixel have been converted to the XYZ colour system and then to sRGB, before finally being Gamma-corrected to best represent the appearance of Uranus to the average human observer. The same intensity scale has been used for all figures in this composite image.

viewing angles using NEMESIS (Irwin et al. 2008), where for these simulations we used 21 angles in our zenith angle quadrature scheme and 38 Fourier components in the azimuthal decomposition. The computed spectra were then used to simulate the overall reflectivity spectrum of Uranus for different phase angles by interpolating the spectra to the local viewing zenith angle, solar zenith angle, and azimuth angle at each location on the planet and integrating over the disc. The reflectance spectra were converted to disc-integrated spectral irradiance ($\text{W m}^{-2} \mu\text{m}^{-1}$) by multiplying by our standard reference solar spectrum, which was taken to be that of Chance & Kurucz (2010), extrapolated to longer/shorter wavelengths with the solar spectrum of Kurucz (1993). To simulate the visible appearance of Uranus at different phase angles, the interpolated spectra at each location on the planet were convolved with standard XYZ colour-matching functions and then converted to the sRGB colour space as described by Stockman & Sharpe (2000), Stockman (2019), and Irwin et al. (2024). In Fig. 3, we show the simulated ‘true-colour’ appearance of Uranus at phase angles 0° , 30° , 60° , 90° , 120° , and 150° , where the images have been Gamma-corrected to give the appearance of Uranus as would be seen by an average human observer

(see Irwin et al. 2024). As can be seen the apparent colour of Uranus becomes less blue as we go to higher phase angles and the integrated reflectivity drops.⁸

The computed disc-integrated spectra at each phase angle were then convolved with the Voyager/ISS filter functions and also the Voyager/IRIS radiometer responsivity function to calculate filter-averaged reflectivities of Uranus as a function of phase angle. These phase angle calculations are compared in Fig. 1 with the Voyager/ISS observations of Wenkert (2023) (from which phase curves have been extracted; Wenkert et al. 2023) and the Voyager/IRIS observations of Pearl et al. (1990). In addition, simulated phase curves at Strömgren-*b* and -*y* wavelengths are also shown. It should be noted that Voyager observed increasingly equatorial regions of Uranus as it headed to higher phase angles due to the large inclination of Uranus’s axis and the fact that these observations were made near solstice. Since Uranus is known to form a ‘hood’ of increased haze opacity at polar latitudes near solstice, this means that the reflectivities observed by Voyager at different phase angles are weighted to regions of very different aerosol structure, which adds to the complexity of interpreting these phase curves.

It can be seen that the observed variation of reflectivity with phase angle is reasonably well defined in the Clear, Violet, Blue, and Green channels, where the signal-to-noise ratio of the Voyager/ISS observations are good, but is less clear in the UV and Orange channels. The UV and Orange reflectivities are known to be the least reliable observations in this data set, due to increased noise caused by the lower radiances seen in these channels (Fig. 2) and insufficient exposure times. However, it can be seen that the simulated phase curves are in reasonably good agreement with observations, which adds confidence that NEMESIS models the reflectivity of Uranus at different phase angles reliably. Indeed, if we scale our simulations by single factor for each filter (for example for the Clear filter a factor of 0.908 has been applied), it can be seen that the simulations are in good agreement with the shape of the measured phase curves, which suggests that the differences could just be caused by photometric inconsistencies; such channel-to-channel variation was also seen when we analysed Voyager-2 ISS observations of Uranus (Irwin et al. 2024). We thus used our NEMESIS simulations to compute the phase integral q (equation 2) numerically, validating these calculations against a model planet with a uniform perfectly scattering Lambertian surface, for which we computed the expected values of $p = 2/3$ and $q = 1.5$, leading to $A = 1$.

The calculated geometric albedo spectrum $p(\lambda)$ from our model is shown in Fig. 2 and can be seen to be in good agreement with the measured disc-averaged *HST*/STIS albedo spectrum of Karkoschka & Tomasko (2009), from which this model was derived. Fig. 2 also shows the Voyager/ISS channel filter profiles (Danielson et al. 1981), the Voyager/IRIS-radiometer spectral response functions (Hanel et al. 1981), and the Strömgren-*b* and Strömgren-*y* filter functions (Crawford & Barnes 1970). As can be seen, the observed and modelled geometric albedo spectrum of Uranus varies greatly with wavelength, with high albedos seen at visible and UV wavelengths, but decreasing rapidly at longer wavelengths due to the increasing absorption of gaseous methane. Hence, the mean albedo of a filter passband depends strongly on these responsivity curves.

⁸This best-fitting model was also used to generate a revised simulated video of a future possible spacecraft’s approach to Uranus and the descent of an entry probe (<https://www.youtube.com/watch?v=NPZeBLCjI-0>), where this colour variation with phase angle can also be seen.

Table 2. Simulated filter-averaged Bond and geometric albedoes computed from our reference holistic model fitted to observations from 2000 to 2009. The likely errors on these values is discussed in the main text.

Instrument or range	Geometric albedo \bar{p}	Bond albedo \bar{A}	Phase integral \bar{q}
Strömgren- <i>b</i> (467 nm)	0.606742	0.819338	1.35039
Strömgren- <i>y</i> (551 nm)	0.482306	0.647710	1.34295
Voyage/ISS – Clear	0.545037	0.737174	1.35252
Voyager/ISS – UV	0.517394	0.709903	1.37207
Voyager/ISS – Violet	0.564171	0.767374	1.36018
Voyager/ISS – Blue	0.577464	0.779424	1.34974
Voyager/ISS – Green 1	0.474723	0.637848	1.34362
Voyager/ISS – Green 2	0.471953	0.634109	1.34359
Voyager/ISS – Orange	0.430355	0.578334	1.34385
<i>HST</i> /STIS (0.3–1.02 μm)	0.344325	0.465665	1.35240
Voyager/IRIS Radiometer	0.233810	0.316006	1.35155
0.2–1.9 μm	0.268850	0.364617	1.35621
0.2–2.5 μm	0.258426	0.350479	1.35620
0.2–100 μm	0.248886	0.337540	1.35620

From the computed irradiance spectra $I(\lambda, \alpha)$ ($\text{W m}^{-2} \mu\text{m}^{-1}$) at wavelength λ and phase angle α we calculated the phase integral spectrum $q(\lambda)$, which is also shown in Fig. 2. It can be seen that our computed phase integrals lie in the range 1.3 to 1.4 at visible wavelengths, reducing to 1.2 to 1.3 at longer methane-absorbing wavelengths, but increasing in the methane windows. This is expected as the main reflection is from the Aerosol-2' layer at ~ 1.5 bar, which is modelled as being composed of micron-sized particles that are rather forward scattering at these wavelengths, thus increasing q . We calculated filter-averaged geometric and Bond albedoes using the following equations:

$$\bar{p} = \frac{\int f(\lambda)I(\lambda, 0)d\lambda}{\int f(\lambda)S(\lambda)d\lambda}, \quad \text{and} \quad \bar{A} = \frac{\int f(\lambda)q(\lambda)I(\lambda, 0)d\lambda}{\int f(\lambda)S(\lambda)d\lambda}. \quad (4)$$

Here, $S(\lambda)$ is the solar irradiance spectrum for a perfectly reflecting Lambertian disc of Uranus's size and distance from the Sun, and $f(\lambda)$ is the filter sensitivity profile. It is important to stress that we computed these filter-averaged albedoes by taking ratios of the filter-averaged irradiances, rather than filter-averaging the albedo spectra $p(\lambda) = I(\lambda, 0)/S(\lambda)$ and $A(\lambda) = q(\lambda)I(\lambda, 0)/S(\lambda)$ using:

$$\bar{p} = \frac{\int f(\lambda)p(\lambda)d\lambda}{\int f(\lambda)d\lambda}, \quad \text{and} \quad \bar{A} = \frac{\int f(\lambda)A(\lambda)d\lambda}{\int f(\lambda)d\lambda}. \quad (5)$$

The spectra of both Uranus and the Sun can be seen to vary greatly with wavelength in Fig. 2. Hence, while $\bar{p} \sim \bar{p}$ and $\bar{A} \sim \bar{A}$ for narrow filters, it is not a good approximation for the wide filter passbands we consider here.

Our computed averaged albedoes for a range of filters and wavelength ranges are listed in Table 2. In this table, the quoted effective phase integrals are computed as $\bar{q} = \bar{A}/\bar{p}$. Since the reflectivity of Uranus decreases greatly with wavelength, the filter-averaged albedoes for the Voyager/IRIS-radiometer filter are significantly lower than those of shorter wavelength filters. It can also be seen in Fig. 2 that the IRIS radiometer filter biases against the reflectivity at very short wavelengths. If instead we calculate the albedoes using a filter that is uniformly transmitting from 0.2 to 1.9 μm , we find significantly higher albedoes. However, even this calculation ignores some reflected radiance, as the solar spectrum is non-negligible at longer wavelengths and Uranus still has some reflectivity. To address this, we first matched a combined reference IRTF/Spex and *JWST*/NIRSpec spectrum to the computed $I(\lambda, \alpha)$ radiance spectra

from 1.5 to 1.6 μm and used these scaled spectra to extend the calculation from 1.9 to 2.5 μm . Secondly, since ~ 3.7 per cent of the Sun's irradiance is at wavelengths longer than 2.5 μm , we extended the computed spectra further to 100 μm , assuming that Uranus has insignificant reflectivity at wavelengths longer than 2.5 μm (i.e. we assumed Uranus's reflectivity at wavelengths longer than 2.5 μm to be zero). We believe this to be a sensible assumption as Uranus's observed reflectivity is already very small at 2.5 μm , and aerosol particles would have to be very large and the layers optically thick to have significant backscatter at longer wavelengths, which is not consistent with current atmospheric haze models (e.g. Irwin et al. 2022). As can be seen, these extensions have the effect of slightly decreasing the computed albedoes, but they are still 6 per cent greater than the Voyager/IRIS estimate. Integrating over all wavelengths (0.2–100 μm) we conclude that in the period 2000–2009: $p^* = 0.249 \pm 0.007$, $q^* = 1.36 \pm 0.03$, and $A^* = 0.338 \pm 0.011$. Our estimate for q^* is well within the range of previous estimates (Table 1), but as we will see in the next section p^* and A^* vary significantly with time, and this variation must be accurately accounted for in order to arrive at robust estimates of the orbital-mean Bond albedo and radiative balance.

Averaging our simulated spectra over the Voyager/IRIS-radiometer responsivity function, we calculate values of $\bar{p}_{\text{IRIS}} = 0.234$, $\bar{A}_{\text{IRIS}} = 0.316$, and $\bar{q}_{\text{IRIS}} = 1.35$. With regard to possible errors, the 2000–2009 observations that our model is derived from are believed to be accurate to 1 to 2 per cent, and we are able to fit to these data to within this precision. The error on the calculation of the phase integral is harder to check, but the shape of our phase curves looks consistent to first-order with the Voyager phase curves shown in Fig. 1. Assuming 2 per cent for the observation and fitting errors and adding these in quadrature, this amounts to ± 2.8 per cent for p , giving $\bar{p}_{\text{IRIS}} = 0.234 \pm 0.007$. Assuming 2 per cent uncertainty for q gives $\bar{q}_{\text{IRIS}} = 1.36 \pm 0.03$ and combining these errors in quadrature gives $\bar{A}_{\text{IRIS}} = 0.316 \pm 0.011$. Our estimates for these IRIS albedoes from 2000 to 2009 are thus consistent with the values determined by Pearl et al. (1990) in 1986 of $\bar{p} = 0.231 \pm 0.048$ and $\bar{A} = 0.322 \pm 0.049$. However, we will see in the next section that the albedo of Uranus is known to have decreased significantly from 1986 to the early 2000s, which leads us to suspect that the albedoes of Pearl et al. (1990) may be underestimated. This conclusion is also consistent with Table 1, where it can be seen that values of Pearl et al. (1990) are lower than the previous three studies considered.

4 SEASONAL CYCLE MODELLING

Our Bond albedo estimate comes from our modified holistic model fit to *HST*/STIS, IRTF/Spex, and Gemini/NIFS observations made from 2000 to 2009 and near equinox when the albedo of Uranus is known to be significantly lower than it is near solstice (Lockwood 2019). To compare more directly with Voyager-2 observations we need to correct for this albedo change. Furthermore, in order to best estimate the orbital-mean Bond albedo, we need to accurately model the average absorbed solar energy during Uranus’s orbit about the Sun.

Irwin et al. (2024) found that the seasonal variations in reflectivity determined from the Lowell Observatory observations of Lockwood (2019) could be moderately well approximated by a model where polewards of 40°S and 40°N an additional opacity ($\tau = 5$ at 800 nm) of conservatively scattering micron-sized particles is added to the Aerosol-2 layer at ~ 1.5 bar to simulate the effects of Uranus’s polar ‘hood’. Although this was used by Irwin et al. (2024) to model just Strömgren-*b* and Strömgren-*y* reflectivity variations, we assumed the same model could be used here to simulate the variations in reflectivity at all other wavelengths.

To make the new simulation, we took our reference modified holistic model and computed the Minnaert nadir and limb-darkening spectra $I_0(\lambda)$ and $k(\lambda)$. Then, adding an additional opacity ($\tau = 5$ at 800 nm) of conservatively scattering particles to the Aerosol-2 layer at 1.4 bar with the same mean radius of 0.8 μm we computed new Minnaert spectra $I_{0\text{Pole}}(\lambda)$ and $k_{\text{Pole}}(\lambda)$, more appropriate for polar regions. Then, for one orbit about the Sun, and using geometry ephemeris data from JPL Horizons,⁹ following the procedure of Irwin et al. (2024), we computed the radiance at each point on Uranus’s disc [including Uranus’s polar flattening, which Irwin et al. (2024) found to have a small effect on the overall reflectivity] as seen from Earth using the Minnaert model for both cases, combining them depending on latitude as:

$$(I/F) = (1 - f)(I/F)_{\text{Ref}} + f(I/F)_{\text{Pole}}, \quad (6)$$

where the weighting factor f was assumed to vary with latitude ϕ (in degrees) as:

$$f = (1 + \tanh(10\pi(|\phi| - 40)/180))/2. \quad (7)$$

This distribution gives $f = 0$ at the equator and $f = 1$ at the poles, with a cross-over latitude of 40°. We then integrated the computed spectra over the disc to determine the disc-averaged geometric reflectivity in the various filters. Finally, to account for the fact that our reference reflectivity spectrum was calculated from disc-averaged data, rather than equatorial data as assumed by Irwin et al. (2024), and thus already partly includes the hood as seen in 2002, the final reflectivities were multiplied by a factor of 0.99 to ensure a good match to the observed Strömgren-*b* and Strömgren-*y* Lowell Observatory reflectivities of Lockwood (2019). Our simulated Strömgren reflectivity curves are compared with the observed Lowell reflectivities in Fig. 4 and also to *HST*/WFC3 observations from 2014 to 2022 (Irwin et al. 2024). This figure is very similar to fig. 13 of Irwin et al. (2024) and shows moderately good agreement between the observed and simulated curves between 1985 and 2022. However, the observed reflectivities are lower than those simulated from 1950 to 1985 (especially at green wavelengths) for reasons that are currently unclear. Irwin et al. (2024) suggest that the reflectivity may be dependent on Uranus’s mean distance from

the Sun. Uranus was closest to the Sun in 1965 and furthest in 2009 and Irwin et al. (2024) suggest that increased solar flux may lead to a higher concentration of dark chromophore particles near perihelion, causing asymmetry in the reflectivity cycles.

The apparent correlation between giant planet atmospheric colouring agents, atmospheric dynamics, and solar irradiation is under active investigation. Pérez-Hoyos et al. (2009) purported that colour changes over Oval BA, one of Jupiter’s largest storms, might have been caused by increased insolation after the material was lofted to a higher altitude, in turn increasing the rate of photochemical reactions affecting the colour change. A correlation between chromophore darkness and UV fluence was also noted by Carlson et al. (2016), who performed laboratory experiments to find a candidate for Jupiter’s red chromophore (Carlson et al. 2016) and may indicate that the deeper redness of Jupiter’s Great Red Spot is caused by the haze particles being trapped in a vortex and exposed to sunlight for extended periods. This correlation between UV irradiation and chromophore colour is currently under further investigation (Carlson et al. 2023).

To see if the observed asymmetry in the seasonal curves might affect our orbitally averaged heat balance calculations, we also generated an empirical fit to the Strömgren-*y* curve using:

$$R'(t) = \overline{R(t)} - 0.005 + 1.5(R(t) - \overline{R(t)}) - 0.1(S(t) - 1), \quad (8)$$

where $R(t)$ is our simulated Strömgren-*y* seasonal curve (shown in Fig. 4), $\overline{R(t)}$ is its orbital average, and $S(t) = F_{\text{Sun}}(t)/F_{\text{Sun}0}$, where $F_{\text{Sun}}(t)$ is the solar insolation curve, shown later in Fig. 5, and $F_{\text{Sun}0}$ is the insolation when Uranus is at a distance of 19.2 au from the Sun.

Fig. 4 also shows reflectivity curves calculated when averaged over the Voyager/ISS filters, the Voyager/IRIS radiometer response function, and finally when averaged over all calculation wavelengths (0.2–1.9 μm). It can be seen that the amplitude of the reflectivity variations increases as we go to longer wavelengths, due to the fact that at longer wavelengths the polar hood becomes clearer and less masked by Rayleigh scattering. Averaging over all calculation wavelengths $\bar{p}_{(0.2-1.9\mu\text{m})}$ can be seen to vary from roughly 0.27 to 0.29 over Uranus’s year. We used these curves to estimate how much more reflective Uranus was in 1986 (during the Voyager-2 encounter) compared with the year of our *HST*/STIS observations in 2002, and phase integral curves including these factors are also shown in Fig. 1 as dashed lines. In particular, averaging over the Voyager/IRIS radiometer response function we estimate that Uranus should have been more reflective by 9.5 percent in 1986 than it was in 2002. Hence, with this additional correction we estimate the likely geometric and Bond albedos in 1986, averaged over the IRIS response function to have been $\bar{p}_{\text{IRIS}} = 0.256$ and $\bar{A}_{\text{IRIS}} = 0.346$, which are considerably larger than the estimates of Pearl et al. (1990), but still within the estimated error of their values. Finally, Fig. 4 also shows an additional 0.2–1.9 μm curve derived by scaling the empirical Strömgren-*y* seasonal curve by the mean ratio between the computed curves integrated over the Strömgren-*y* filter and over the range 0.2 to 1.9 μm . This is used later to investigate how much the asymmetry in the observed Strömgren-*y* seasonal curve might affect the orbitally averaged heat balance.

Using the calculated seasonal curve for $\bar{p}_{(0.2-1.9\mu\text{m})}$ we computed the seasonal cycle of the Bond albedo using $A = pq$, taking $\bar{q}_{(0.2-1.9\mu\text{m})}$ from Table 2 to be 1.36. In the previous section, we saw that the Bond albedo estimated from averaging from 0.2 to 1.9 μm is likely lower than the total bolometric Bond albedo by a factor of 1.08 and hence our final bolometric albedo $\bar{A}_{(0.2-100\mu\text{m})}$ is corrected by this factor, assuming it does not change with season. However, to compute the total power absorbed by Uranus, we need

⁹<https://ssd.jpl.nasa.gov/horizons/>

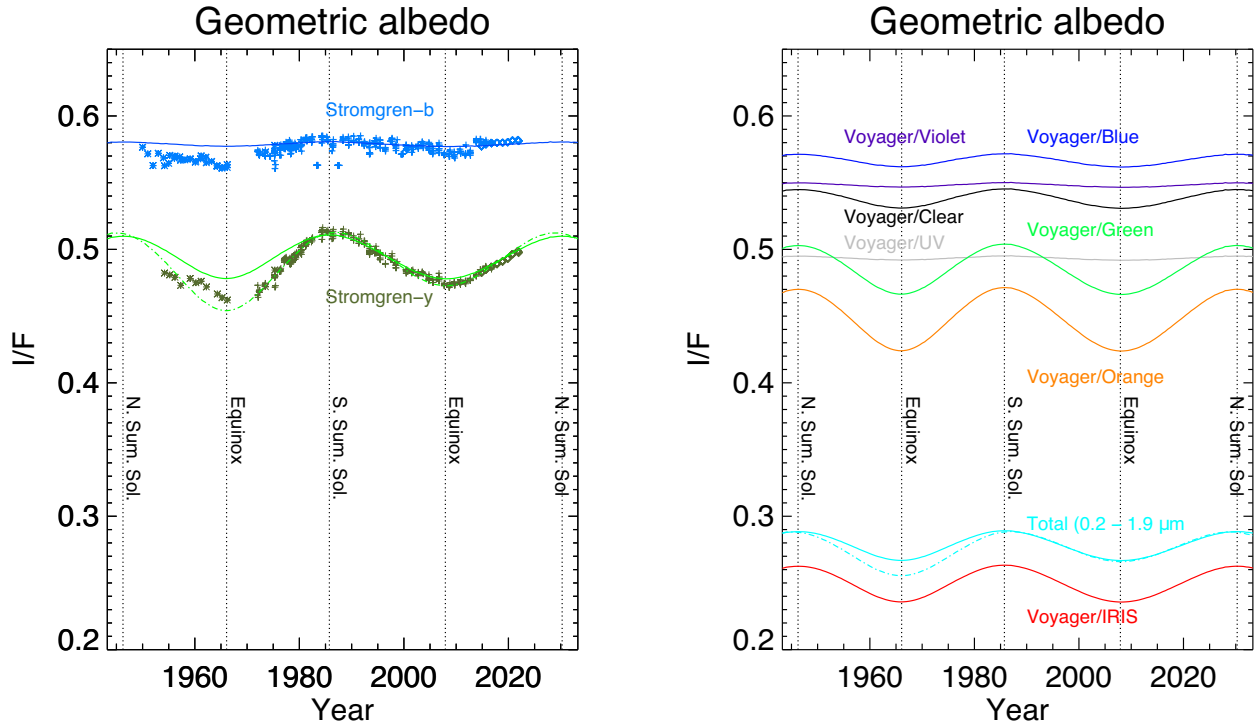


Figure 4. Seasonal variation in reflectivity of Uranus averaged over different filter profiles using a modified seasonal cycle model of Irwin et al. (2024), which has an additional component ($\tau = 5$ at 800 nm) of conservatively scattering particles of mean radius $0.8 \mu\text{m}$ added to the Aerosol-2 layer at 1.4 bar at polar latitudes. Left: the calculated reflectivity curves (solid lines) averaged over the Strömgren-*b* and Strömgren-*y* filters are compared with the measured disc-averaged reflectivities calculated by Irwin et al. (2024) from the magnitude observations of Lockwood (2019), recorded directly in these filters from 1972 to 2016 (crosses) or converted from Johnson B and V observations from 1950 to 1966 (asterisks), and equivalent *HST*/WFC3 observations from 2016 to 2022 (diamonds). The dash-dot green line shows an empirically constructed albedo curve that better matches the observed Strömgren-*y* seasonal curve. Right: the calculated reflectivity curves averaged over the different Voyager/ISS filters are shown, together with the curves averaged over the Voyager/IRIS-radiometer sensitivity function, or over all computed wavelengths ($0.2\text{--}1.9 \mu\text{m}$). For this last calculation, the dash-dot cyan line shows an alternative total curve scaled from the empirically fitted Strömgren-*y* seasonal curve.

to consider not only how the Bond albedo varies with season, but also that the incident solar flux varies during Uranus’s eccentric orbit by approximately ± 10 per cent, as can be seen in Fig. 5(A). In addition, the area of Uranus presented to the Sun varies since Uranus is significantly oblate and has a high axial inclination. Hence, the presented area is maximum at the solstices and minimum at the equinoxes, varying by approximately ± 1 per cent. Combining these effects we can compute the total solar power intercepted by Uranus and divide this by the planet’s total surface area to determine the average incident solar flux per unit area of the atmosphere, F_{Sun} . We find that this varies from 0.84 to 1.01 W m^{-2} during Uranus’s orbit (Fig. 5C). Fig. 5(B) shows how the Bond albedo varies with time, either averaging over all wavelengths ($0.2\text{--}100 \mu\text{m}$), or averaging over the Voyager/IRIS radiometer filter. Combining these effects, we can compute the bolometric value of the absorbed flux per unit area F_{abs} , which we show in Fig. 5(C). The bolometric value of this can be seen to vary from 0.558 to 0.674 W m^{-2} , with a mean value of 0.604 W m^{-2} . The confidence of this value depends on several factors:

- (i) The accuracy of the *HST*/STIS, Gemini/NIFS, and IRTF/SpeX observations fitted to by Irwin et al. (2022), which we estimated previously to be 2.8 per cent.
- (ii) The accuracy of our seasonal cycle model, which we show to be consistent with the Lowell observations of Lockwood (2019), but which we have extrapolated here initially to $1.9 \mu\text{m}$ in our

radiative transfer calculation. The accuracy of this extrapolation is more difficult to evaluate, but since the bulk of Uranus’s reflectivity comes from visible wavelengths, we believe that 2 per cent is a conservative estimate of the likely error.

- (iii) The accuracy of using the same phase integral value of $q = 1.36$ for all seasons and all wavelengths. We model the poles to be more reflective to match the seasonal cycles, but we have no way of assessing how much the phase integral varies with season. Again, to be conservative, we assume here 2 per cent for this uncertainty.

- (iv) The accuracy of the factor of 1.08 we used to convert \bar{A} calculated from 0.2 to $1.9 \mu\text{m}$ to all wavelengths ($0.2\text{--}100 \mu\text{m}$). This was computed from our reference holistic model, which did not have a separate polar hood and hence may in reality vary with season. To account for this we again conservatively estimate this value to be accurate to 2 per cent.

- (v) The observed asymmetry in the seasonal reflectivities reported by Lockwood (2019), but not reproduced in our simulations. To attempt to quantify this error, we also made calculations using the empirical $\bar{p}_{(0.2\text{--}1.9 \mu\text{m})}$ curve mentioned earlier and shown in Figs 4 and 5, which we report below.

All other elements in our calculation come from well-established solar spectra, or geometrical considerations, which we estimate to have errors insignificant with those listed above. Adding all these components in quadrature we arrive at a likely percentage error for A^* and P_{in} of ± 4.5 per cent. Hence, including all factors we find orbital

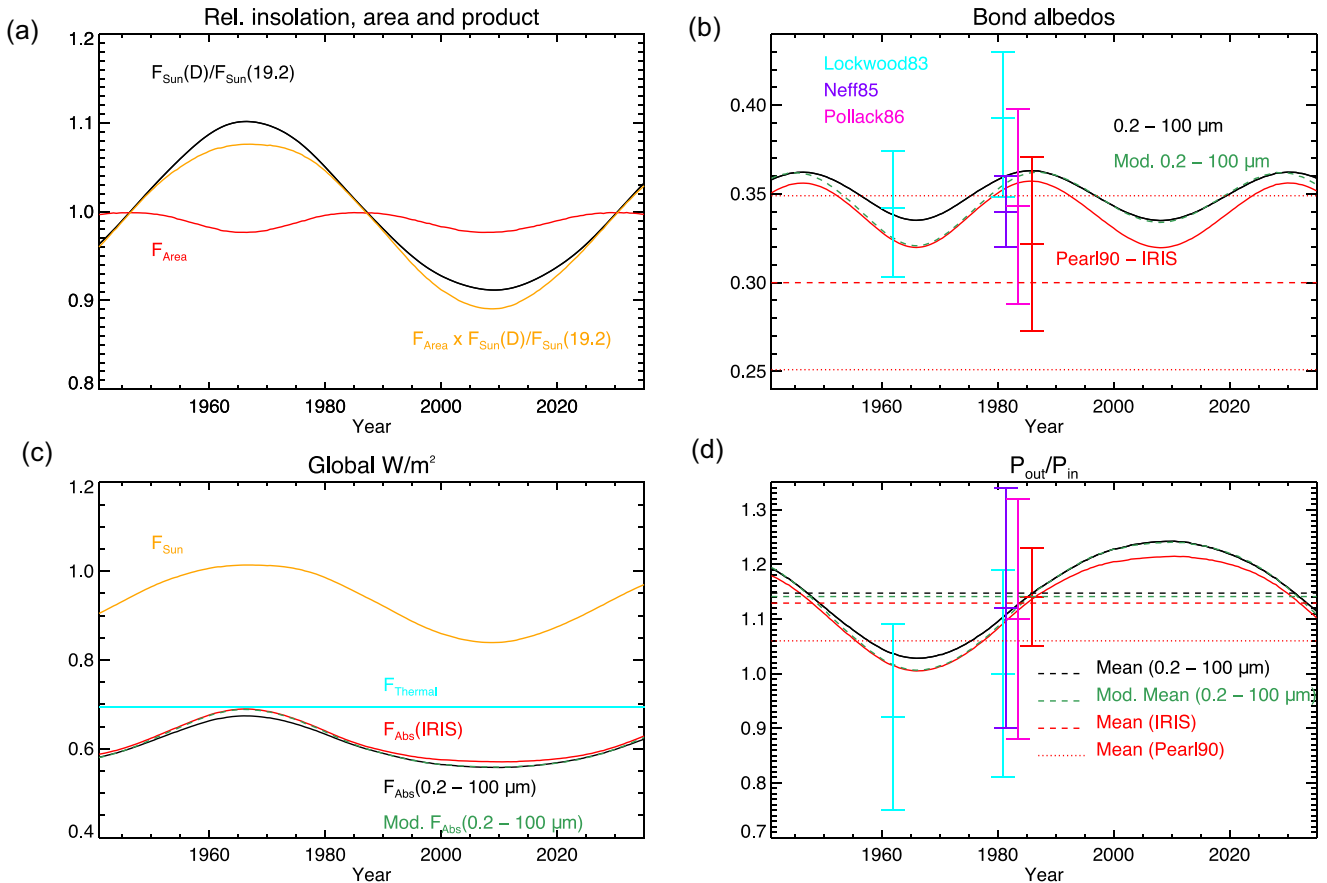


Figure 5. Calculations of Uranus’s orbitally averaged Bond albedo and heat budget. Panel A: orbital variation of the incident solar flux at Uranus relative to the standard Uranus distance of 19.2 au, compared with the projected area of Uranus relative to a sphere with Uranus’s equatorial radius; the remaining line is the product of the two. Panel B: computed variation of Bond albedo with season, averaged over all wavelengths (0.2–100 μm , black), or averaged over the Voyager/IRIS radiometer function (red). These variations are compared with estimates of the bolometric Bond albedos listed in Table 1 from Lockwood et al. (1983), Neff et al. (1985), Pollack et al. (1986), and Pearl et al. (1990), and colour-coded as shown. The orbital-mean Bond albedo from Pearl et al. (1990) is shown as the dashed red line, with error limits shown as red dotted lines. Panel C: seasonal energy budget of Uranus’s atmosphere. The incident solar flux per unit area of Uranus’s atmosphere is shown, while the other lines show the solar fluxes absorbed by Uranus’s atmosphere assuming Bond albedo variations calculated over all wavelengths (0.2–100 μm), or averaged over the Voyager/IRIS radiometer function. These fluxes are compared with the assumed outgoing thermal flux of $0.693 \pm 0.013 \text{ W m}^{-2}$ (Pearl et al. 1990). Panel D: seasonal variation of the $P_{\text{out}}/P_{\text{in}}$ flux ratio, averaged over all wavelengths (0.2–100 μm , black), or over the Voyager/IRIS radiometer function (red). The orbital mean values are also shown as dashed lines and compared with the previous estimates listed in Table 1 and using the same colours as in Panel B. In panels B–D, the dashed green line shows the 0.2–100 μm calculations derived from the empirically adjusted $\bar{\rho}_{(0.2-1.9\mu\text{m})}$ curve shown in Fig. 4.

mean averages of $\bar{A}^* = 0.349 \pm 0.016$ and $P_{\text{in}} = 0.604 \pm 0.027 \text{ W m}^{-2}$. To determine the flux ratio $P_{\text{out}}/P_{\text{in}}$ we assume P_{out} to be $0.693 \pm 0.013 \text{ W m}^{-2}$, as determined by Pearl et al. (1990) from Voyager/IRIS spectrometer observations, and we conclude an orbital mean of $P_{\text{out}}/P_{\text{in}}$ of 1.15 ± 0.06 (i.e. 4.9 per cent), varying during Uranus’s year from 1.03 to 1.24.

To see what effect the observed asymmetry of Uranus’s reflectivity curves (Lockwood 2019) might have on these calculations, we repeated them using the empirically adjusted $\bar{\rho}_{(0.2-1.9\mu\text{m})}$ curve shown in Fig. 4 and find values of $\bar{A}^* = 0.345 \pm 0.016$, $P_{\text{in}} = 0.607 \pm 0.027 \text{ W m}^{-2}$, and $P_{\text{out}}/P_{\text{in}} = 1.14 \pm 0.06$, which are well within the error limits of our formal calculations and show that the observed asymmetry in the observed Strömgren- γ seasonal curve likely does not significantly affect Uranus’s heat balance.

Finally, if we instead average over the IRIS filter function we find orbital-mean values of $\bar{A}_{\text{IRIS}} = 0.338 \pm 0.015$, $P_{\text{in}} = 0.614 \pm 0.027 \text{ W m}^{-2}$, and $P_{\text{out}}/P_{\text{in}}(\text{IRIS}) = 1.13 \pm 0.06$. These values are within error of those calculated by averaging from 0.2 to 100 μm , showing

that the assumption made by Pearl et al. (1990) that $A_{\text{IRIS}} = A^*$ is reasonable when averaged over a whole Uranus year. The values are consistent with those of Pearl et al. (1990) of $\bar{A}_{\text{IRIS}} = 0.300 \pm 0.049$ and $P_{\text{out}}/P_{\text{in}} = 1.06 \pm 0.08$, but have smaller error bars. We have taken great care in our study to conservatively estimate our error sources, and we have also taken great care to estimate how the albedo of Uranus varies over the year and how varying orbital distance and projected cross-sectional area affects the absorbed solar power. Even with our conservative error assumptions, our much more detailed and robust calculation leads to error bars on $P_{\text{out}}/P_{\text{in}}$ that are smaller than those estimated by Pearl et al. (1990) and hence we conclude that our solution is better constrained and more robust.

5 DISCUSSION

We have concluded in this study that the bolometric (i.e. averaged over all wavelengths) value of $P_{\text{out}}/P_{\text{in}}$ for Uranus is significantly greater than 1.0 and thus that Uranus is not in thermal equilibrium

with the Sun. Hence, Uranus appears to be much less of an outlier compared with the other planets than previously thought, although the Uranian value of $P_{\text{out}}/P_{\text{in}}$ is still significantly smaller than for the other three giant planets, for which values of $P_{\text{out}}/P_{\text{in}} \sim 2$ are generally accepted.

Our findings of a significant source of internal heat for Uranus are more in line with the expectations of radiative–convective modelling studies. Marley & McKay (1999) find an internal heat flow less than $P_{\text{int}} = 0.06 \text{ W m}^{-2}$ results in model Uranus tropospheres that are significantly cooler than those observed by the Voyager radio-occultation experiment (Lindal et al. 1987). Assuming $P_{\text{out}} = 0.693 \pm 0.013 \text{ W m}^{-2}$, the value of $P_{\text{out}}/P_{\text{in}} = 1.06$ determined by Pearl et al. (1990) gives $P_{\text{int}} = 0.04 \text{ W m}^{-2}$, which would appear to be too small. However, using our new value of $P_{\text{out}}/P_{\text{in}} = 1.15$ gives $P_{\text{int}} = 0.10 \text{ W m}^{-2}$, which is more consistent with Marley & McKay (1999). More recently, Markham & Stevenson (2021) look at how condensation effects may have affected the thermal evolution of Uranus and Neptune. Such effects can inhibit convection, but the apparent absence of an internal source of heat in Uranus defied explanation in their study. Most recently, Milcareck et al. (2024) have performed radiative–convective modelling of the stratospheres of Uranus and Neptune using the holistic aerosol model of Irwin et al. (2022). Although this paper does not make estimates of internal heat flow, the value of the Bond Albedo derived for Uranus of 0.35 is very similar to what we have determined here of 0.349 ± 0.016 , adding confidence to our estimate.

We find that Uranus is furthest from thermal equilibrium near the northern summer equinox period, a period which has just passed (equinox was in 2007), which may help to explain the increased storm cloud activity seen in Uranus’s atmosphere near this time. It may be that increased solar heating at other times helps to stabilize the atmosphere by heating the upper levels and suppressing convection from the interior. This may thus help explain why Uranus appeared to be so quiescent and dormant during the Voyager 2 flyby in 1986. If this interpretation is correct, then it is likely that the planet’s storm activity will now decrease as the incident solar flux increases and the upper levels of Uranus’s atmosphere become warmer. In addition, as Uranus now starts to move closer to the Sun and the insolation starts to increase again, the Lowell Observatory data of Lockwood (2019) would suggest that Uranus should become slightly darker heading towards the next equinox in 2049 than it was in 2007. Continued observations are essential to confirm whether Uranus’s seasonal albedo cycle really is asymmetric.

In addition to the seasonal cycles considered here, there is also a small variation in Uranus’s albedo detected in the Lowell Observatory data of Lockwood (2019) on the time-scale of the solar cycle (i.e. ~ 11 yr; Aplin & Harrison 2017). There are two mechanisms suggested to account for this solar modulation: nucleation on to ions or electrons created by galactic cosmic rays (GCR), or UV-induced aerosol colour changes, which are also suggested to affect the albedo of Neptune (e.g. Aplin & Harrison 2016; Roman et al. 2022). Given that a slower seasonal variation of albedo is seen in the Lowell Observatory data (Lockwood 2019) that may be related to Uranus’s distance from the Sun, this suggests that the second explanation may be more likely in this case. However, such solar-cycle variations are too rapid and too small to affect our orbital-mean estimates here.

Finally, our estimate for $P_{\text{out}}/P_{\text{in}}$ is critically dependent on the assumed value of the outgoing thermal flux, which we have assumed to be $P_{\text{out}} = 0.693 \pm 0.013 \text{ W m}^{-2}$ (Pearl et al. 1990) and to not vary with season. If, however, there has been a miscalibration of this value, or if the outgoing thermally emitted flux varies during the Uranian year then this will affect the flux ratio, as indeed would any

unmodelled seasonal variations in the phase integral q^* , which we have here assumed to have a constant value of $q^* = 1.36 \pm 0.03$.

6 CONCLUSIONS

In this study we used the modified ‘holistic’ aerosol model of Irwin et al. (2022), James et al. (2023), and Irwin et al. (2024) to compute a new estimate of the bolometric Bond albedo of Uranus in the early 2000s. Then, using a seasonal model of Uranus based on Irwin et al. (2024), we have calculated how this albedo varies with season and make a new estimate of the orbitally averaged mean solar flux absorbed by Uranus, comparing this with the assumed outgoing thermal flux of $0.693 \pm 0.013 \text{ W m}^{-2}$, determined from Voyager-2/IRIS observations by Pearl et al. (1990). We arrive at the following conclusions.

(i) Averaging from 0.2 to 100 μm , and using a fixed phase integral value of $q^* = 1.36$ at all seasons we find an orbital-average bolometric Bond albedo of $\bar{A}^* = 0.349 \pm 0.016$, noting that this varies significantly during the year from 0.335 to 0.363.

(ii) Combining these computed reflectivity curves with solar flux and projected area orbital variations, and averaging from 0.2 to 100 μm we find the total mean solar power absorbed by Uranus to be $0.604 \pm 0.027 \text{ W m}^{-2}$, varying during the year from 0.558 to 0.674 W m^{-2} .

(iii) Assuming the orbital mean outgoing thermal flux of $0.693 \pm 0.013 \text{ W m}^{-2}$ from Voyager-2/IRIS (Pearl et al. 1990), we find, averaging from 0.2 to 100 μm , that $P_{\text{out}}/P_{\text{in}} = 1.15 \pm 0.06$, varying during the year from 1.03 to 1.24.

(iv) If we instead use the empirical geometric albedo curve derived from the observed asymmetric Strömgren- y seasonal curve of Lockwood (2019) and extrapolate to 0.2–100 μm we find values of $\bar{A}^* = 0.345 \pm 0.016$, $P_{\text{in}} = 0.607 \pm 0.027 \text{ W m}^{-2}$, and $P_{\text{out}}/P_{\text{in}} = 1.14 \pm 0.06$, which are well within the error limits of our formal calculation. Hence, we conclude that the observed asymmetry in the observed Strömgren- y seasonal curve does not significantly affect Uranus’s heat balance.

(v) Finally, if we instead average over the Voyager/IRIS-radiometer responsivity function (Hanel et al. 1981), we find values of $\bar{A}_{\text{IRIS}} = 0.338 \pm 0.015$, $P_{\text{in}} = 0.614 \pm 0.027 \text{ W m}^{-2}$, and $P_{\text{out}}/P_{\text{in}} = 1.13 \pm 0.06$. These are just within the error limits of our 0.2–100 μm calculations and show that assuming $A_{\text{IRIS}} = A^*$, as was done by Pearl et al. (1990), is a reasonable approximation.

While we have used our simulations to greatly improve the estimated values of \bar{A}^* and P_{in} for Uranus, our estimate of $P_{\text{out}}/P_{\text{in}}$ is critically dependent on the assumed value of the outgoing thermal flux $P_{\text{out}} = 0.693 \pm 0.013 \text{ W m}^{-2}$ (Pearl et al. 1990). We have assumed this value to be correct and have also assumed that it does not vary with time. If, however, there has been a miscalibration of this value, or if, in fact, the outgoing thermally emitted flux varies with season, then this will affect the flux ratio. We thus recommend that the value of the outgoing thermal flux from Uranus’s atmosphere be restudied, perhaps using more recent ground-based and *JWST* observations. In the meantime, assuming $P_{\text{out}} = 0.693 \pm 0.013 \text{ W m}^{-2}$ we conclude that although Uranus is not in thermal equilibrium with the incident solar flux, $P_{\text{out}}/P_{\text{in}}$ is still significantly less than for the other three giant planets, for which values of $P_{\text{out}}/P_{\text{in}} \sim 2$ are generally accepted. We also note that the high eccentricity of Uranus’s orbit leads to significant change in the incident solar flux, which if correlated with the production of dark photochemical haze products may help to explain the asymmetry in Uranus’s seasonal albedo cycle observed in Lowell Observatory observations

(Lockwood 2019). To explore this further, the next step in this project will be to analyse *Hubble* visible wavelength data from 1994 through 2025 to gain a clearer understanding of how Uranus's reflectivity changes at other wavelengths while the planet moved from just before the northern spring equinox towards northern summer solstice.

ACKNOWLEDGEMENTS

We are grateful to the United Kingdom Science and Technology Facilities Council for funding the early stages of this research (Irwin: ST/S000461/1). This review includes observations made with the NASA/ESA *Hubble Space Telescope* obtained from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under NASA contract NAS 5–26555. These observations are associated with STIS programme(s) GO9035, GO9330, GO12894, GO14113, and WFC3 programmes GO13937, GO14334, GO14756, GO15262, GO15502, GO15929, GO16266, GO16790, GO16995. AAS was supported by a grant associated with continuing programme GO13937.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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