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The bolometric Bond albedo and energy balance of Uranus

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The radiative heat balance of Uranus has long been a mystery amongst the solar system giant planets. Jupiter, Saturn and Neptune all emit much more power thermally (P_{out}) than they absorb from the Sun (P_{in}) with P_{out}/P_{in} having values of 1.7 to 2.6. This shows that all three planets retain a considerable amount of heat left over from formation, which they are still slowly radiating away into space. In stark contrast, Uranus appears to be unexpectedly cold. Measurements made by Voyager-2 determined a radiative heat balance ratio of only P_{out}/P_{in} = 1.06 ± 0.08 (Pearl et al. 1990), which is consistent (to within error) with Uranus being in thermal equilibrium with the Sun and thus, perhaps, having no heat of formation left over at all. Meanwhile, Voyager-2 determined a radiative heat balance ratio for Neptune of P_{out}/P_{in} = 2.61 ± 0.28 (Pearl and Conrath, 1991), which is the largest ratio determined for any of the giant planets.

How can the radiative heat balance ratios of Uranus and Neptune, the solar system's 'Ice Giants' be so different? And is Uranus really in thermal equilibrium with the Sun, with no internal heat of formation left over? To answer this last question, we have performed a modelling study (Irwin et al., 2025) using our NEMESIS radiative transfer tool (Irwin et al., 2008) and a newly developed 'holistic' atmospheric model of the aerosol structure in Uranus's atmosphere, based upon observations made by HST/STIS, Gemini/NIFS and IRTF/SpeX from 2000 – 2009 (Irwin et al., 2022). Taking our fitted aerosol structure and extrapolating our calculations to all wavelengths, we have made a new estimate of the bolometric geometric albedo of Uranus during the period 2002 – 2009 of p* = 0.249. The bolometric geometric albedo is the fraction of sunlight reflected by the planet back towards an observer in line with the Sun, but to determine heat balance we need to calculate the bolometric Bond Albedo, which is the fraction of sunlight incident on the planet that is scattered into all directions. With our holistic aerosol model and NEMESIS, we can calculate the appearance of Uranus to an observer at any phase angle from the Sun, and integrating these modelled curves over all phase angles we can calculate the phase integral, q, which relates the geometric albedo, p, to the Bond albedo, A, through the relation A = pq.

From this modelling we determine a bolometric (i.e., integrated over all wavelengths) phase integral of □□ = 1.36, and thus a bolometric Bond albedo of □□ = 0.338 for the period 2002 – 2009. However, to determine the overall radiative heat balance of Uranus, we first need to account for the seasonal variation in □□, which changes significantly during Uranus's year due to the formation of a polar 'hood' of haze over the summer pole, which becomes thicker and more observable near the solstices. In addition, in terms of energy balance, we also need to account for the fact that the incident sunlight at Uranus varies significantly during its eccentric (e = 0.046) orbit about the Sun by ±10%. Also, since Uranus is significantly oblate and has high polar inclination, there is a small,

but significant difference in its projected area towards the Sun between solstice and equinox, which affects the total power of sunlight received by the planet.

To estimate the orbital-average bolometric Bond albedo and radiative heat balance we used a simple seasonal model, developed by Irwin et al. (2024) to be consistent with the disc-integrated blue and green magnitude data from the Lowell Observatory from 1950 – 2016 (Lockwood, 2019). Taking all hood thickness/visibility, distance and projected area effects into account, we model how Uranus's reflectivity and heat budget vary during its orbit and determine a new orbital-mean average value for the bolometric Bond albedo of □□ = 0.349 ± 0.016 and estimate the orbital-average mean absorbed solar flux to be □$_{in}$□ = 0.604 ± 0.027 W m^{-2}. Assuming the outgoing thermal flux to be □$_{out}$□ = 0.693 ± 0.013 W m^{-2}, 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 ± 0.06. We find, however, that there is considerable variation of the radiative heat balance with time due mainly to Uranus's orbital eccentricity, which leads P_{out}/P_{in} to vary from 1.03 near perihelion, to 1.24 near aphelion. We conclude that although P_{out}/P_{in} is still considerably smaller than for the other giant planets, Uranus is not in thermal equilibrium with the Sun.

References.

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