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P5 2 A Rayleigh Good Time: How Different Stars Paint Alien Skies

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Abstract

We investigate the colour of a clear sky under main-sequence stars of different classifications. A previous paper, 'Mr. Blue Sky', outlined a method which associated the sky colour with a single peak wavelength. Ward et al. [2] predict a green sky for an unscattered spectrum, and an ultraviolet sky for a scattered spectrum. Instead, we use the scattered blackbody spectrum to calculate chromaticity, finding blue skies for A0–M0 stars and a white sky near 3300 K. We find that the chromaticity coordinates for the Earth's sky are $x = 0.236 \pm 0.003$ and $y = 0.237 \pm 0.004$, which suggests our method predicts a bluer sky than observed.

Introduction

Molecules in the atmosphere scatter solar radiation, making the sky appear blue in the daytime. Rayleigh scattering favours short wavelengths [1], so considering scattering alone would suggest a violet sky on Earth. This is not what we see, so this raises an important question on how the colour of a spectrum should be determined.

A previous PST paper [2] made an estimate of the colour of the sky by finding the peak wavelength of the scattered spectrum using Wien's displacement law. However, the peak wavelength found by this calculation could lie outside of the visible range. We instead suggest that the perceived colour depends on the entire spectrum and the wavelength-dependent response of the human eye.

The International Commission on Illumination (CIE) colour-matching functions provide a way of modelling how a standard observer responds to light of different wavelengths [3]. By integrating the spectrum using these functions, the chromaticity of light can be found, allowing a colour to be assigned to the entire spectrum.

Sky Colour Model

We start with modelling the star as a blackbody with temperature T, and the atmosphere is assumed to be optically thin.

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_\mathrm{B} T)} - 1}. \tag{1}$$

Here, h is Planck's constant, c is the speed of light and k_B is Boltzmann's constant [5]. We then consider the Rayleigh dependence [1].

$$S_\mathrm{scat}(\lambda, T) \propto B_\lambda(\lambda, T)\lambda^{-4}. \tag{2}$$

To find what the human eye would perceive, the spectra were weighted using the CIE 1931 colour-matching functions [3]. The resulting tristimulus values were calculated by integrating the spectrum against each colour-matching function.

$$X = \int S_{\mathrm{scat}}(\lambda, T)\bar{x}(\lambda)\, d\lambda, \tag{3}$$

with corresponding expressions for Y and Z. The chromaticity coordinates were calculated using equation 4.

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z}. \tag{4}$$

This normalisation removes the brightness dependence, leaving only the chromaticity.

The integrals were evaluated using the trapezium rule on a 1 nm wavelength grid. Stellar temperatures from 2500 to 10000 K were swept in 100 K steps.

Results and Discussion

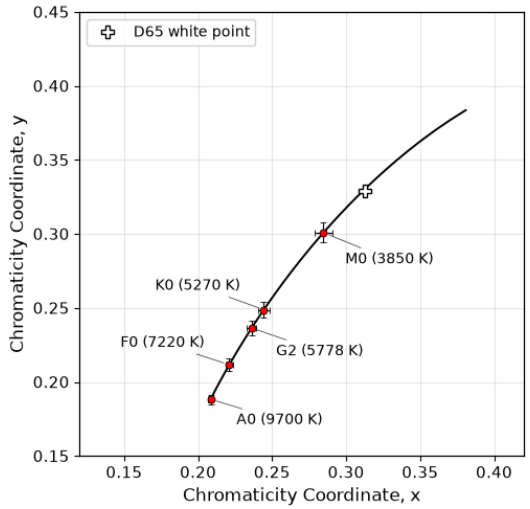


Figure 1: The CIE 1931 chromaticity coordinates of the Rayleigh-scattered blackbody spectra for 2500–10000 K. The stellar classes A0–M0 are shown [4]. Error bars represent the uncertainties in x and y, and the cross illustrates the white point [3].

We found that increasing stellar temperature moves the calculated chromaticity towards the blue region of the diagram. At 3300 K, the curve passes through the white point. Stars cooler than 3300 K give a muted yellow, while hotter stars give a saturated blue.

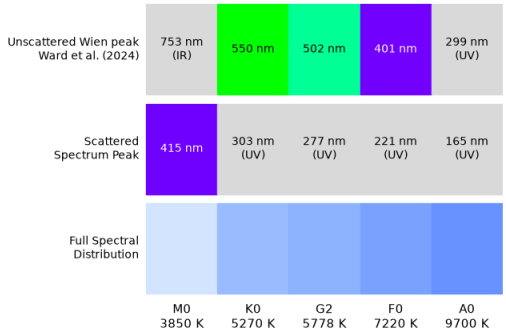


Figure 2: A direct comparison of the peak-wavelength method against the full spectral distribution for different temperatures.

Figure 2 shows that the peak-wavelength method [2] assigns mostly ultraviolet wavelengths to the scattered spectra, despite the full spectra producing blue light.

An interesting finding is that hotter stars lead to a more saturated blue. Our Sun is a G2 star, which results in coordinates of $x = 0.236 \pm 0.003$ and $y = 0.237 \pm 0.004$, which is below the real values ($x \approx 0.264$, $y \approx 0.277$ [6]) by approximately 10% for x and y by 14%. This implies that the model predicts a bluer sky than is observed.

The uncertainty in effective temperature was taken from the average spread within each spectral subclass [4], giving 3.3% or ± 0.003 in x. The difference between our predicted and observed chromaticities is ten times larger. This is likely due to excluding the effects of multiple scattering and atmospheric geometry and assuming that the Sun is a perfect blackbody [7].

Conclusion

This paper concludes that peak wavelength cannot be used as a proxy for colour, whether scattering is considered or not. We found that the full spectrum predicts blue skies across A0–M0 stars, a white sky near 3300 K, and muted yellow for temperatures below 3300 K. Using the Sun in this model gives values bluer than what is seen, so including multiple scattering would be a natural next step.

References

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