How the Sun Paints the Sky

The generation of its colour and luminosity

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Introduction: the 19th century context — science and painting

The appearance of a brilliantly clear night sky must surely have stimulated the curiosity of our earliest ancestors and provided them with the foundation upon which their descendants built the entire edifice of science. This is a conclusion that would be dramatically affirmed if any one of us were to look upwards in clear weather from a location that is not polluted by artificial light: an increasingly rare possibility now, but one that provides a welcome regeneration of the sense of wonder.

What happened when our ancient ancestors gazed instead at the sky in daylight or twilight? It is difficult to gauge from written evidence as there was such variation in the language of description among different cultures (see "Sky in a bottle" by Peter Pesic. MIT Press, 2005. ISBN 0-262-16234-2). The blue colour of a cloudless sky was described in a remarkable variety of language, but the question of its cause most often remained in the realm of a superior being. Its nature did concern the Greek philosophers but they appeared to describe surfaces and objects in the language of texture rather than colour: they did not have a word for blue. It was only during the last millennium that thinkers really tried to get to grips with the problem, with Leonardo da Vinci, Isaac Newton and Johann Wolfgang von Goethe all applying themselves. It was not easy however, and no real progress was made until the mid-19th century when there was a focus of the greatest scientific minds of the time on the problem of both the colour and the what was then the novel property of polarisation of the light. Sir John Herschel, in 1862, remarked that these two properties were "the two great standing enigmas of meteorology". With the involvement of John Tyndall, the third Baron Rayleigh (John W Strutt), James Clerk Maxwell and subsequently Albert Einstein, he might well have used the word 'science' to replace just 'meteorology'. Herschel expressed the dilemma by pointing out that Tyndall's observations were clearly not consistent with the current theory of reflection derived by David Brewster and pointed, perceptively as it turned out, towards the need for some other explanation that would result in sunlight being reflected from air and changed in colour.

The story of cracking the problem of the blue sky is beautifully told in the book "Why is the Sky Blue" by Götz Hoeppe (English translation, Princeton University Press, 2007. ISBN2-8724-0485) who takes us up to the present day and explains how deeply entwined the story became with the concept of molecules and their sizes and numbers, reaching deep into the heart of physics and chemistry and contributing to the variety of estimates of Avogadro's number — which is related to the number and mass of atoms or molecules in a specific volume of gas.

Figure 1. ***The Fighting Temeraire*, tugged to her last berth to be broken up, is an oil painting by the English artist Joseph Mallord William Turner, painted in 1838 and exhibited at the Royal Academy in 1839. Turner, who was benefiting from the revolution in synthetic pigment production at the time, was interested in the science and discussed with Michael Faraday the choice of pigments that would be stable in a polluted city. The colour palette shown here was computed with an atmospheric model for twilight conditions.** ***(Photo taken in the National Gallery with permission)***

Meanwhile, as it was gradually dawning on the scientists of the day that they might be progressing towards a major revolution in physics and chemistry and that science was not actually 'all wrapped up', the artists were getting along with painting the sky 'as it was' rather than how it was idealised.

The hugely enriched palette of colours emerging from developments in chemistry during this period enabled Turner to produce works that would shock his current audience but delight those in the future. His *Ulysses Deriding Polyphemus* (1829) was condemned as 'colouring run mad' at the time. However, both this and *The Fighting Temeraire* (1838, Figure 1) reveal his powers of observation and perception. He could not yet rely on science for this as the latter was painted four years before the birth of Lord Rayleigh who would develop the solution to the problem raised by Tyndall's experiments and who would thus enable us to understand how the colours arise. Turner was, however, plugged into the science of the day: the Royal Academy and the Royal Society shared the same building and it seems that Turner

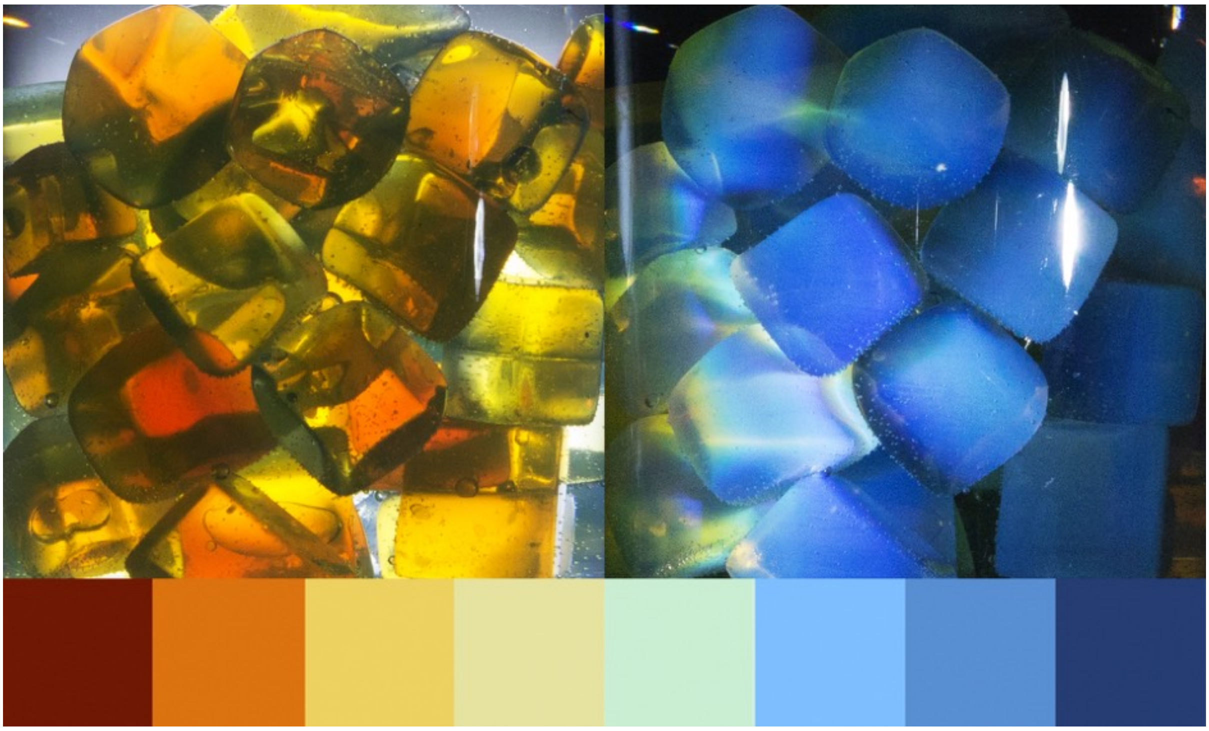

Figure 2. Two images of a jumble of opalescent, but otherwise colourless, glass cubes in a jar containing water to reduce the refractive index difference with the surrounding medium. The image on the left is backlit with white light and that on the right is illuminated from the front right. The cubes on the left are seen mostly in transmitted light, while those on the right are scattering light towards us and seen against a dark background. The swatches along the bottom are colours computed from an atmospheric model which includes both Rayleigh and small particle (Tyndall) scattering. ***(Image Credit: Fosbury/Ward/Girkin, Durham University)***

was fascinated by science and often discussed new developments with Michael Faraday who advised him on the pigments that would survive the pollution in a smoky London.

Turner's choice of palette for the Temeraire sunset can be reproduced with a rather simple experiment using a type of glass that is easily obtained as a 'stone' cheap enough for children to buy in a gift shop. This is variously called 'opal' or 'opalescent' glass which contains tiny (really tiny) crystals of fluoride salts which have been dissolved in the glass mix and subsequently manipulated with heat treatment to result in two phases with different refractive indices (Figure 2). The Rayleigh/Tyndall scattering of light within the glass makes an excellent analogue model of how the atmosphere produces the twilight colours in a way that will be discussed later.

The physical origins of colour in the sky

Let us remain in the 19th century for a while longer and consider the origin and demise of a photon of light starting in the Sun and ending on the retina of our eye on Earth. This photon will be conceived deep in the solar core from the energy associated with its very high temperature of about 15,000,000K. This was calculated just after mid-century by von Helmholtz and Lord Kelvin (the originator of the absolute temperature scale referred to as 'K' or 'kelvin'[1]) who realised that this high temperature must result from the gravitational energy released by the collapse of the Sun from its parent constituents. As they did not yet know about the nuclear reactions that will keep the Sun shining for a lifetime of around ten billion rather than 30 million years it would take for the Sun to radiate away its all gravitationally produced heat energy, there was great and often heated debate about the age of the Sun and the Solar System. This debate involved both Darwin and the geologists who were convinced that 30 million years was insufficient to explain what they observed.

For our original super-high energy photon that cannot escape directly, it takes about 30 thousand years to diffuse, with multiple transformations to many lower and lower energy photons along the way, before being born again at a visible wavelength and released from the solar photosphere as to commence its journey across the Universe.

Not all of these photons will reach the relatively empty space between the stars however. They have to run the gauntlet first of the remaining tenuous layers of the solar atmosphere, chromosphere and corona and then to dodge all the other members of our Solar System. The

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[1] The kelvin has the same magnitude as a degree centigrade but its zero point is at -273.15 °C, known as *Absolute Zero.*

atmosphere of the Sun is quite transparent to most visible colours/wavelengths, but the atoms in the gas, such as hydrogen, iron, calcium, sodium, magnesium etc., all have their own set of specific colours at which they will readily absorb a photon of light should one come close enough. Many emerging photons will be captured by one or other of these atomic absorptions and leave gaps at particular wavelengths in the spectrum of sunlight. These gaps are known as Fraunhofer lines and these also became a major focus of study in this scientifically thrilling century.

We have lost some photons, but there are a lot remaining and the vast majority of those will now leave the Solar System. It takes a little over five hours for these photons to make their escape past Pluto during which time a tiny fraction will be intercepted by a planet. To reach the Earth as 'daylight' takes only about eight minutes.

If we follow a photon as it approaches the Earth and ask what is likely to happen to it, we can begin to see what will produce the colours. The photon will not so much 'hit' the atmosphere but, in a cloudless sky, it will weave very slightly between molecules and tiny

Figure 3. Translated to a real sunset/rise seen from Earth orbit, Rayleigh's Fish (made from similar opalescent glass) gazes on our planet and considers what we now know about twilight colours. The light enters through the fish's eye and scatters the blue light first, followed by the sequence of yellow and red. ***(ISS photograph Credit: NASA/ESA)***

particles of liquid, dust, ice and even pollen, as it approaches the surface. These slight wiggles in path are due to the small variations in air density, and hence refractive index, that arise because of the turbulence which is the bane of astronomers' efforts to obtain sharp images from ground-based telescopes without the help of the modern adaptive-optics technology that is now becoming widely used in large telescopes.

With the Sun reasonably high in the sky and the air clear, most — but not all — of the incoming photons will reach the ground and some might even enter your eye and collaborate with a few others to trigger a photoreceptor in the retina and send a signal to the visual cortex. The colour you see after receiving a large number of photons will depend on those photons that do not make it through. Which ones are these likely to be?

The two processes that affect the photons in the atmosphere are, firstly, scattering: that is the redirection of a photon away from its original direction in space. There are several flavours of scattering, only two of which are important for painting the sky. They are both what we call 'elastic' scattering processes which means that the redirection does not change the wavelength of the photon. If you want to think of this in terms of billiard balls, you would have to imagine that the ball that you were bouncing off was so heavy that it did not move on being struck by the incoming ball which just changed its direction, but not its energy.

Individual air molecules result in the scattering of light that Rayleigh went on to explain mathematically towards the very end of the century, and so understand the process in terms of Maxwell's theory of electromagnetism. This theory applies to scattering particles that are very much smaller than the wavelength of the light that is being scattered, in this case, molecules, mostly N_2 but also O_2. The characteristic of Rayleigh scattering is that it depends strongly on the wavelength of light and will scatter many more blue photons than red ones: the strength depends on the inverse fourth power of the wavelength and so blue light at 400nm will scatter 9.4 times more often than red light at 700nm. The preference for scattering blue light before red is clearly shown by Rayleigh's Fish in Figure 3. Rayleigh's scattering theory did indeed show that Tyndall was seeing light 'reflected' from air as John Herschel had surmised!

The other scattering process is from particles that are bigger than molecules and closer to the dimension of the light wavelength. This is the case for most of the aerosols that we find in a reasonably clear atmosphere. The mathematics is more complicated than for Rayleigh and is known a Mie scattering theory after Gustav Mie who developed it early in the 20^{th} century. For a representative mixture of aerosols found in reasonably clear air, the scattering remains stronger in the blue but the variation with wavelength is much less extreme and the blue (400nm) is stronger than the red (700nm) by just a factor of 2 with an inverse power of around 1.3 instead of the 4 for Rayleigh.

This difference between Rayleigh and aerosol (Mie) scattering allows a great richness of variation in the appearance of the sky, especially at twilight when the path length of sunlight is much longer. Differences in the density of aerosols and the natural variations in their size and shape, that cause a change in the power index away from 1.3, can vary the colour palette dramatically.

The other important difference between Rayleigh and Mie scattering is in the dependence of the scattering direction with respect to the original direction of photon travel. While the air molecules scatter fairly (but not exactly) equally in all directions, the larger aerosols scatter most strongly in the forward direction. This is why, on a hazy day, the Sun is surrounded by a blindingly white light that can extend over an angle much larger than the solar diameter on the sky. In contrast, notice that on a very clear day, especially at high altitude, the Sun is surrounded by the only faintest of glare. Some aerosols can scatter strongly backwards as well as forwards.

As well as their effects on the colour of the sky, these scattering processes paint a complex pattern of polarisation on the sky which is fascinating and, as alluded to above, was pivotal in understanding the process. However, that is the subject of another talk/article!

What is the effect of these two types of scattering on the stream of photons arriving from the Sun? They both preferentially scatter blue light from the incoming beam of sunlight and this light is redirected to create the blue sky, but we shall return to that later. If you are on the ground bathed in sunlight, the colour will thus appear redder and somewhat fainter than it would to an astronaut on a Space Station.

The second process that lies in wait for the solar photons entering the atmosphere is called absorption. Here the photon terminates its existence by passing its energy to an atom, molecule or particle where it is most often converted to heat. It will therefore not reach our eye but it will leave tell-tale evidence in the spectrum of skylight as what we call a *telluric* (arising from Earth) absorption line or band. There are a number of such absorption features appearing in the visible spectrum of skylight, but most of the stronger ones are near or beyond the red limit of our vision. There is one important exception however, and that results from ozone, a type of oxygen molecule that resides mostly high in the atmosphere and contains three rather than the more usual two atoms. This absorption, known as the *Chappuis Band*, is very considerably weaker than the ozone absorptions that protect planetary life from damaging ultraviolet radiation, but it shows itself with increasing strength as the Sun nears the horizon and photons have to travel through a much longer atmospheric path before

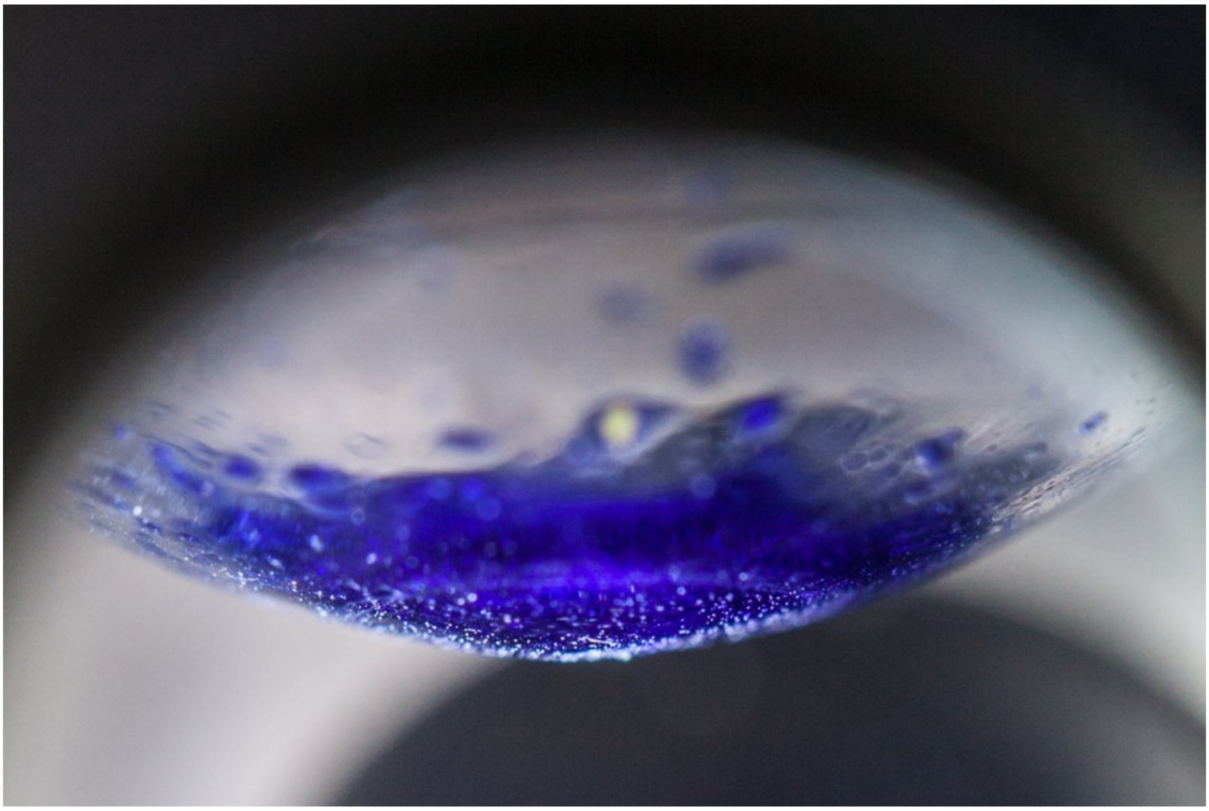

Figure 4. A photograph of liquid ozone showing its rich 'ultramarine' colour. This gas in the ozone layer between altitudes of about 12 and 40 km acts like a giant blue filter covering the sky at dusk and dawn. The blue colour is seen whether the sky is cloudy or not, and the physical process that causes it is entirely different from the Rayleigh scattering producing the daytime clear blue sky. ***(Photograph courtesy of the BIPM (Bureau international des poids et mesures)***

reaching the ground. It has a dramatic effect on the colour of the sky during twilight: it changes the daytime Rayleigh blue of a clear sky into a radically different and deeper ozone blue that is the origin of the the term *L'Heure Bleue*, The Blue Hour, used by artists to describe the special light after the Sun has set or before it rises.

The scattering blue and the ozone absorption blue act in different ways which results in the fact that the sky in daytime is only blue when it is clear. When clouds cover the sky during the day, they mix the reddened sunlight with some of the blue that has been stolen from the sunbeams and distributed over the whole sky, resulting in a grey overcast that is somewhat bluer than sunlight. At twilight however, the ozone acts like a blue filter (Figure 4) covering the whole sky and this makes the clouds blue as well. Our eyes tend to mask this phenomenon because our visual system adapts to the changing colour, meaning that you are not as aware of this radical change to the blue light as your camera is if you switch off the 'auto white-

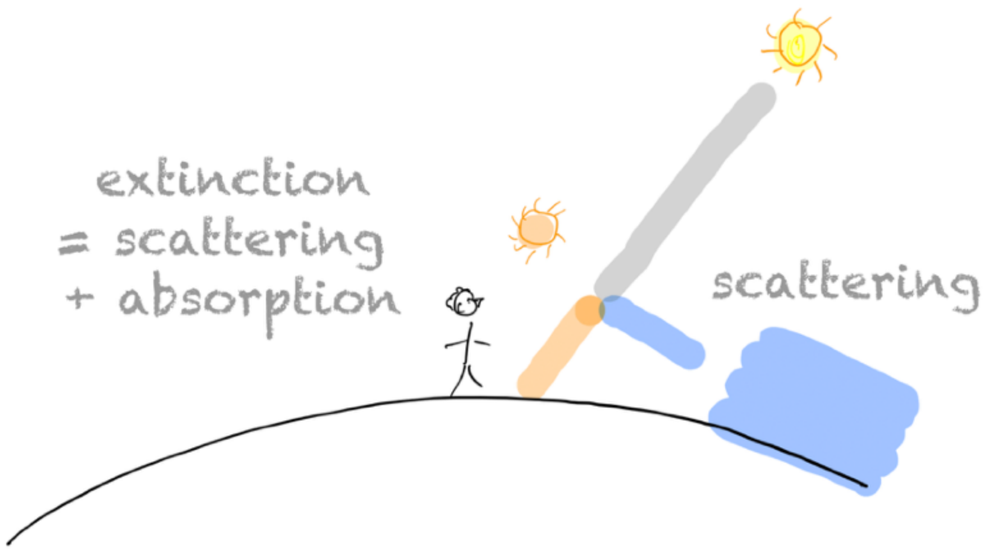

Figure 5. The concept of extinction. As the sunlight enters the atmosphere, some of the light — predominantly blue — is scattered away from its course to form the blue sky. As the remaining light reaches ground level it appears redder to an observer there than to an astronaut seeing it from space. In addition to the scattering, some ozone absorption of orange light becomes apparent as the Sun approaches the horizon.

balance'. Try it half an hour after sunset and the pictures will be so blue that you will think there must be an error!

The sum of the scattering and absorption processes acting on incoming sunlight is known as *extinction*, a term used in astronomy to represent the fraction of light from a distant object (eg. a star) reaching a telescope after traversing the atmosphere (see Figure 5). This represents the sum of the effects of scattering and absorption, both of which processes remove photons from the beam of light. The extinction of light is calculated using the Beer-Lambert-Bouger (Beer's for short) law after the three scientists who arrived at it at different times and from different applications. The mathematics is quite straightforward and easy to calculate and is based on the observation that the loss of light is proportional to the density ($\boldsymbol{n}$) of the scatterer or absorber multiplied by the path length through the medium, the constant of proportionality being the effective cross-sectional area ($\boldsymbol{\sigma}$) of the particular scatterer or absorber which will depend on wavelength. We call this product $\boldsymbol{\sigma\, n\, l}$ the optical depth ($\boldsymbol{\tau}$) which is dimensionless number. Beer's law then simply states that

$$I/I_0 = e^{-\tau}$$

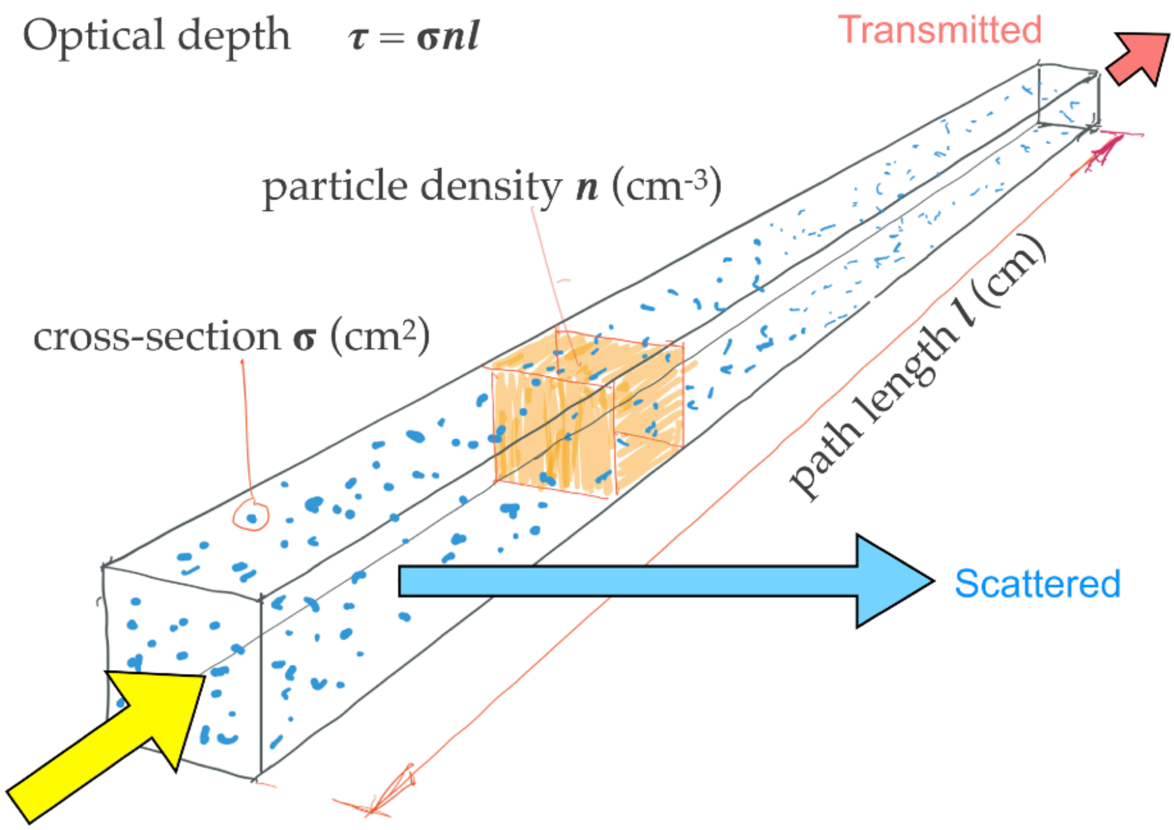

Figure 6. Extinction and optical depth. A cartoon showing a column of air extending through the atmosphere over a path with a length l (cm). The column contains a mixture of molecules and aerosols, each with a particle density of n (cm^{-3}). The absorption or scattering cross-section (cm^2) varies with wavelength. Sunlight entering on the left (yellow arrow) will suffer extinction before leaving on the right (red arrow). Most of the extinction arises from the scattering of light away from the axis of the column (blue arrow).

where τ represents an integral of the product along the path length, I_0 is the initial intensity and I is the incident value at the observer (Figure 6). The complexity arises from the fact that the density of the atmosphere varies with altitude as also does the relative concentration of some of its constituents, notably water vapour and ozone. The cross-section can also vary with temperature and pressure. In practice, the equation above will contain a separate τ for every different scatterer and absorber, each with a different wavelength dependence. To see what the optical depth actually means in practice, see Figure 7.

For our discussion of sky colours, we'll avoid doing the integrals by calling the quantity of atmosphere in a vertical column of clear air above our heads from sea level an airmass (m) of 1 which, when multiplied by the cross-section of the absorber has an optical depth of $\tau(\lambda)$ at each wavelength. The airmass can then be calculated for each solar altitude (a) from 90° at

Figure 7. How does optical depth influence appearance? The left image shows a sea mist obscuring the steeply-sloping shore within a few hundred metres. Water droplets in a mist produce an extinction that it almost independent of colour and the appearance of the cliff-top around the middle of the picture represents an optical depth of about one: you can just see the cliff disappearing into the mist. In the right image, we see the setting sun through an atmosphere producing both Rayleigh and aerosol scattering. Unlike the left image where the cliff is illuminated from outside the cloud, here we see the Sun shining from way beyond the atmosphere. This means that we can still see its sharp outline through an optical depth of significantly greater than one. The atmosphere here has a high aerosol content and the optical depth ranges between a few in the red to larger than ten in the blue, making the Sun appear a deep red.

the zenith to 0° at the horizon. When the Sun is well above the horizon, the value of m can be approximated by $m = 1/sin(a)$. Closer to the horizon than about 10°, corrections need to be made because of the refraction of light in the atmosphere see: Kasten, F. and Young, A. T. (1989). "Revised optical air mass tables and approximation formula". *Applied Optics*. **28** (22): 4735–4738). The airmass to the horizon is close to 40.

The shortcoming of this simplified approach is that we assume the atmospheric gases are well mixed. While we know this not to be the case in practice we can still use the model to get quite realistic colours as the single process of Rayleigh scattering usually dominates. To illustrate how well we can do, Figure 8 shows the application of our extinction model (thin blue line) to an observation (red line) of the solar brightness with the Sun at an altitude of 14° above the horizon. The model only includes the two types of scattering and the ozone absorption and so does not fit the three absorption dips between about 680 and 780nm which are due to water vapour and oxygen. The radiometer used for this measurement has a low spectral resolution and does not show clearly the Fraunhofer lines in the solar spectrum.

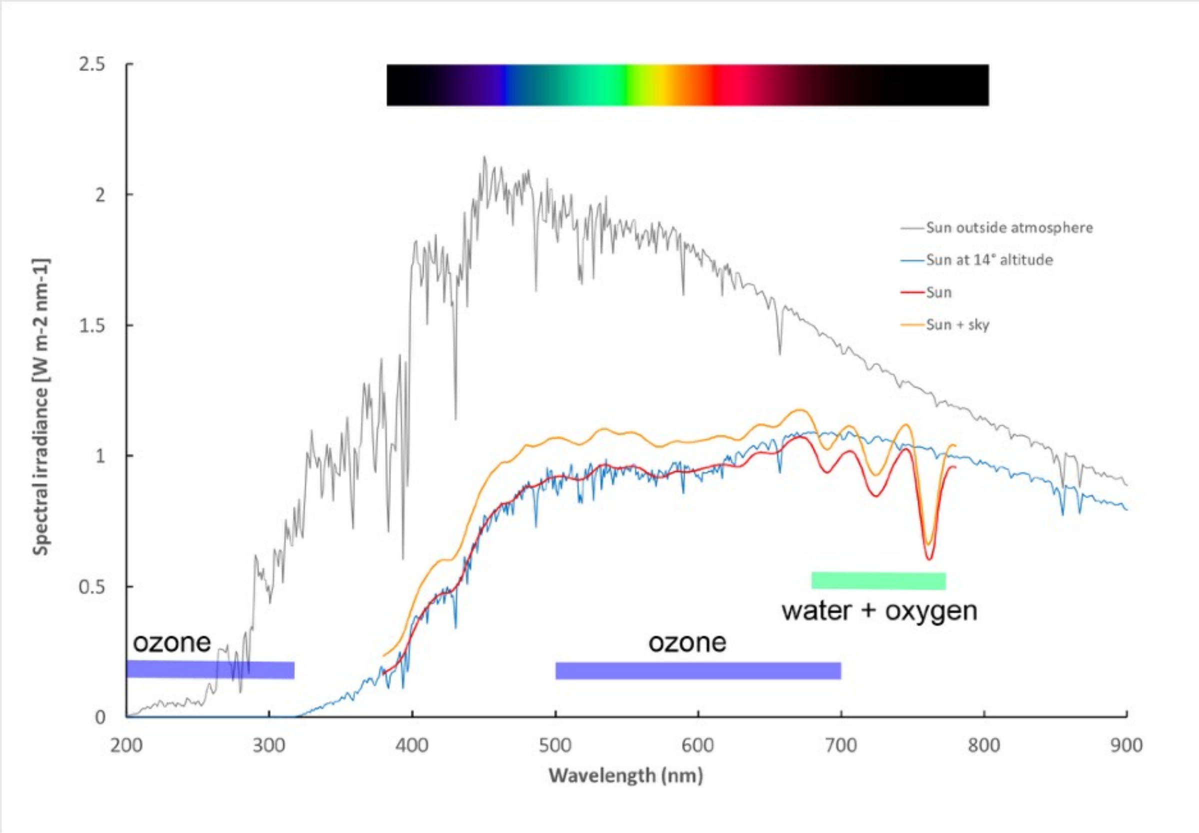

Figure 8. What the spectrum of extinction looks like when the Sun is quite low in the sky. This plot shows as a grey line the brightness (Spectral Irradiance) of sunlight as it arrives at the top of Earth's atmosphere. The brightness is plotted on the vertical axis in units of Watts per square metre per nanometer while the wavelength, in nanometers (billionths of a metre), is plotted on the horizontal axis from the deep ultraviolet on the left to the near-infrared on the right. The red and orange lines show measurements made from close to sea level of the Sun in a clear sky. The Sun was at an altitude of 14° above the true horizon and the measurements, made with a calibrated spectro-radiometer, of the Sun alone (red line, radiance) and of the Sun and sky together (orange line, irradiance) reveal how much light has been diverted by the atmosphere. The thin blue line is the result of an extinction model using Rayleigh and aerosol scattering and ozone absorption that matches well the red line observation. In addition to the telluric absorption from ozone, marked as blue bars, the observations show the beginning of other strong telluric absorptions that extend from the deep red end of the visible spectrum through into the infrared. The three prominent bands here are due to oxygen and water molecules.

Painting the twilight colours

After this discussion of the basic process of atmospheric extinction, we can move on to consider what happens to the light that has been diverted into the sky by scattering. This will allow us to see how the Sun actually does paint the beautiful bands of twilight colour (see Figure 9).

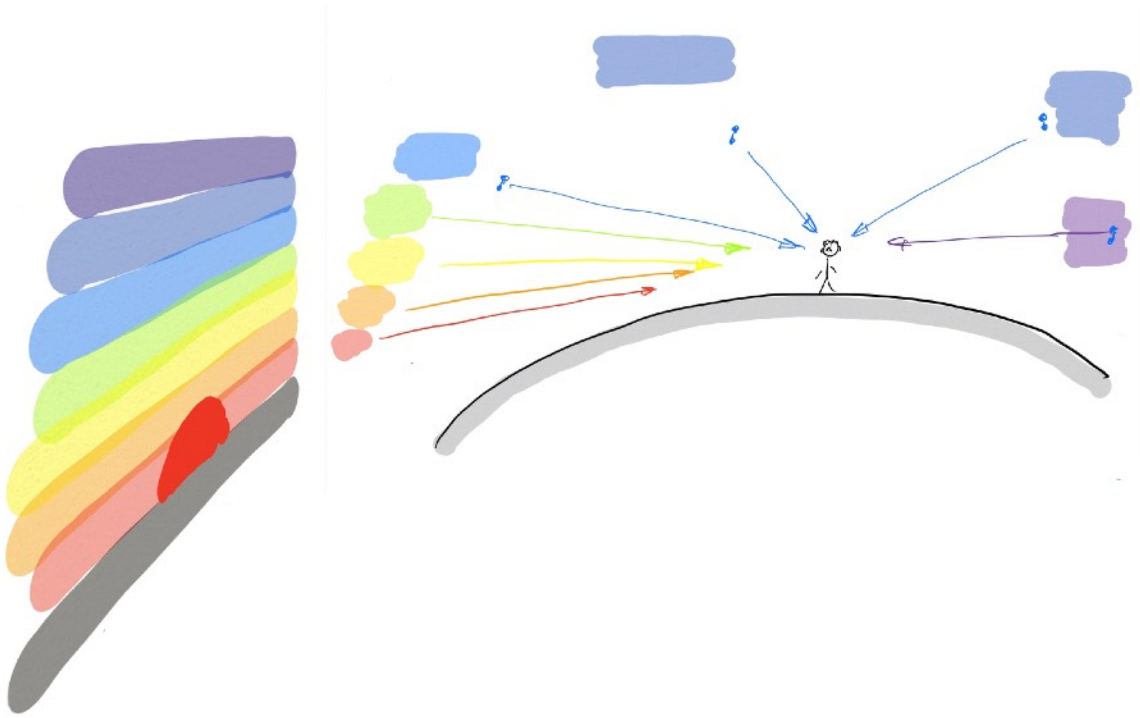

Figure 9. Painting the bands of twilight colour. Light from the low Sun can reach us directly after suffering the extinction arising from a long, almost horizontal path through the atmosphere. It can take many alternative paths, involving a single scattering, from molecules anywhere in the atmosphere that is visible from where we are standing.

We know how we lose sunlight by extinction. How do we calculate the light that comes to us from the sky? Imagine a beam coming from the Sun in a direction which is not directly towards us, but that will enter the atmosphere in a part of the sky that we can see from where we are. As it travels down, it will lose photons to extinction and, of those that are scattered by molecules or aerosol particles, some will come toward us, and a tiny fraction of those will enter our eye to give us an image of the sky in that direction. For each of these photons we need to know the path that it has taken during its passage through the sky. For simplicity, we will assume that it is only scattered once on its way to us. There are some regions of the sky where we need to consider multiple scatterings and that gets complicated, but the effect is small enough to ignore in this simplified discussion of colour.

That means that there are two light paths involved, one before the scattering of light coming from the Sun and one leading from the scatterer to our eye. These paths are not precisely straight. There is another effect here of some importance to astronomers. Light is bent slightly as it travels through the air towards the ground at a slant. As the density changes with altitude, the refractive effect increases, and a ray will be deflected slightly towards the region of higher density. However, the amount it bends depends on the light's wavelength and this means that the images of stars close to the horizon are stretched slightly into short spectra, with red (which bends the least) appearing to us as closer to the horizon. This shift becomes important when precise measurements of star positions are required.

The total extinction along the sequence of these two paths depends on the sum of their scattering and absorption optical depths

$$\tau_{extinction}(\lambda) = \tau_{scattering} + \tau_{absorption}$$

The second part is to determine how much light of each colour is scattered from each parcel of air along the direction to the sky where we are looking. The colour of the scattering is determined by the wavelength dependence of the scattering cross-section (bigger in the blue than in the red) which is already encoded in the optical depth

$$\tau_{scattering}(\lambda) = \tau_{Rayleigh} + \tau_{aerosol}$$

This means that the colour of light we see from any parcel of air anywhere in the sky is determined by the product of the amount of light it scatters and the total extinction. If we forget the absorption for a moment and think of a pure scattering atmosphere, this means the light we see from this piece of sky will be proportional to

$$\tau_{scattering}\, e^{-\tau_{scattering}}$$

We can think of these two terms as a *source* term — the brightness of light scattered from an illuminated parcel of air in the sky which **increases** with scattering strength — and a *sink* term — the light arriving after extinction which, in the negative exponential, **decreases** with scattering strength. This is the key to the beautiful bands of twilight colour! It is the balance between these two terms, one a linear increase and the other an exponential decrease, that modulates the colour over the sky. To see how this works, we just need to look at a graph of this product (Figure 10).

If we look at a *turbid* — a scattering — medium (a glass of diluted milk, a cloud in the sky, a bank of fog, the Earth's atmosphere…) which is illuminated by an external source, the light emerging from it will come predominantly from those parts where the optical depth from the source, through the medium to our eye via a single scattering, is close to one, which is the peak of this graph.

This is illustrated in Figure 11, which shows a sunset and a sunrise, with the Sun just below the horizon, from the Atacama desert in Chile where the sky is very often clear. If we

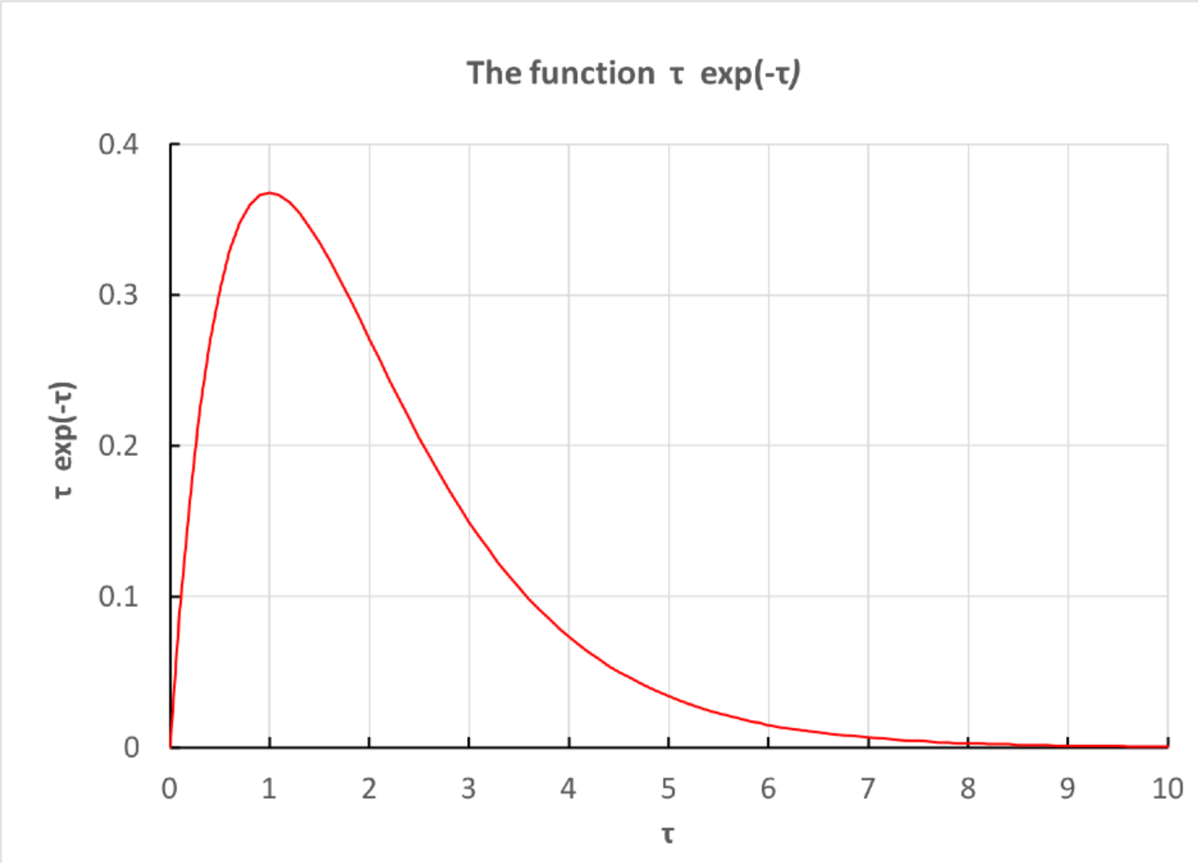

Figure 10. In this graph, as τ increases from zero, there is a rapid rise τo a maximum at τ = 1. This is followed by a slower fall as the exponential extinction begins to dominate. The effect of this behaviour is that when we look at an externally-illuminated cloud of scattering particles, most of the light reaching us from the cloud will originate in regions for which the optical depths to them from the source and from them to us has a combined value of around one. When the value of τ depends strongly on the wavelength of the light, the balance between these two opposing factors will determine which parts of the cloud reflect (scatter) each colour we see.

look at the top pair of paths, we see light entering and taking an almost tangential path high through the atmosphere. If a photon scatters from a molecule high above the ground, it may scatter downwards towards our eye. Although the total length of the path taken by the photon will be long, the total amount of air — the airmass, m — will be relatively small as most of the path will be high up where the density of molecules is small (and the density of aerosols very small!). For this total path to have an optical depth of one, we have to go to a blue colour where the Rayleigh scattering is strongest. Consequently, we see the deep blue twilight sky high in the sky where the air is thinnest.

If, alternatively, we consider a beam of sunlight on a path that grazes the earth through the dense, low atmosphere, it will travel through and scatter within a path with a much larger airmass. It will be only the orange or red photons, with their much weaker scattering, that are

Figure 11. A sunset and a sunrise seen from two observatories in the Chilean Atacama desert. The central column contains a set of swatches computed from a simple single-scattering atmospheric model that illustrates how the colours are formed from the passage of sunlight through different paths to an observer on the ground. The directions to the Sun in each image can be seen from the orientation of the new crescent Moon. ***Image credit: Y. Beletsky (LCO)/ESO***

able to reach us from this direction: the blue light will never make it through. It is apparent that the intermediate paths between these extremes will reach this $\boldsymbol{\tau \sim 1}$ balance in the sequence of subtle pastel colours between blue and red that we see in the images. The effect of absorption processes, notably ozone, is simply added to the model by adding τ_{ozone} to the optical depth term in the exponential sink term.

The presence of the ozone does have a profound effect on the colour of the twilight sky, but this happens through it acting as a filter that removes a large proportion of the orange light in a broad band that extends from the green into the red part of the spectrum. Ozone only appears as extinction (the sink) but not as a scatterer (the source). In fact, without the ozone, the deep purple-blue-grey of the twilight at the zenith above our heads would be much brighter and a pale straw-yellow/grey colour instead.

Figure 12 shows how the colour swatches in the centre of Figure 11 are computed by deriving RGB values for each of the computed spectra as described in the caption. The ozone

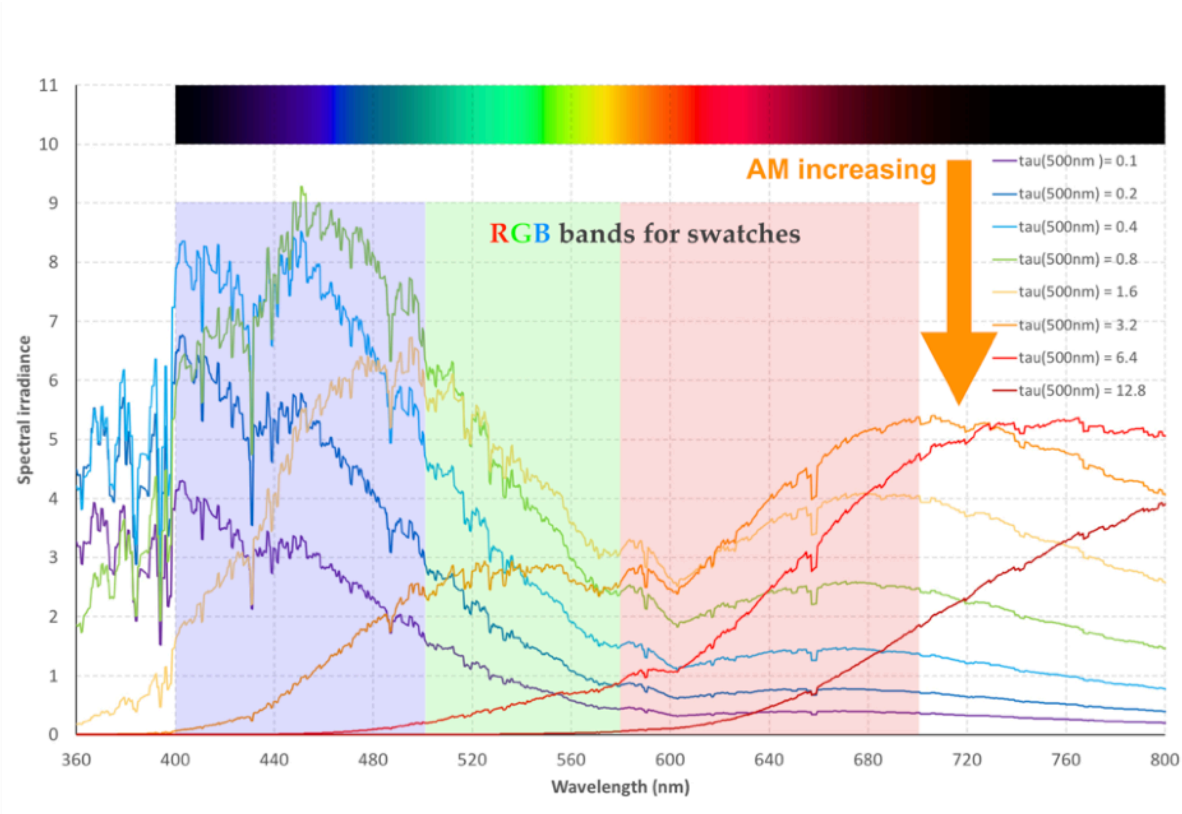

Figure 12. A model of the sequence of twilight colours. These eight spectra were computed using the τ exp(-τ) formalism, with the optical depth varying from 0.1 to 12.8 at a fixed wavelength in the blue-green, to represent an increasing depth of atmosphere (airmass m) penetrated by different light paths. In these calculations, I included the effects of ozone absorption in addition to the scattering discussed in the text. The Chappuis band of ozone results in the broad spectral dip centred near 590nm. Red, Green and Blue (RGB) for each spectrum were calculated by summing the brightness within the coloured regions on the figure. These RGB values were then used to make the coloured swatches shown in Figures 1 and 11.

extinction is included in the calculation and manifests itself as the strong broad dip centred at about 590nm.

This is, of course, a highly simplified model as the light we see is actually a combination of scatterings from parcels of air all along our line of sight. The fact that we have considered just a single parcel does not, however, make a big difference to the colours that we calculate. In reality, the colours will be mixed a little and appear slightly less saturated than in the model.

To summarise this section about the the bands of colour forming in a clear sky as the Sun approaches and sinks below the horizon, let us recall that the physical processes involved are the *scattering* of light from the Sun by molecules and tiny aerosols in the atmosphere with an important contribution from *absorption* by ozone. The colour we see from a particular

Figure 13. Under the shadow of a thundercloud. The distant horizon is illuminated by sunlight which reflects from the underside of the cloud. The horizontal passage of the light under under the cloud is shadowed from the Sun and so does not produce the blue haze that is responsible for aerial perspective, but instead is coloured orange by the extinction. The vegetated ground will also reflect from the cloud base and acquire a green tint to our eyes — but would have a decidedly red tint if one were to use a camera sensitive to the near-infrared. Occasional lightning flashes will also be visible on the cloud (on the right of the image). ***Photo credit: Martin Kornmesser https://www.flickr.com/photos/hipydeus/50065957538/***

direction on the sky is determined by the balance between the strength of the scattering — which makes the sunlight bluer — and the extinction — which makes the light redder — including the additional effect of the absorption of orange light by ozone. This is an extraordinarily beautiful and endlessly variable phenomenon woven from just these three physical processes. To understand this in its full detail and splendour is a very complex computing problem due to the huge number of different paths the sunlight can take towards your eye from different directions and the fact that the atmosphere itself is not homogeneous but varies in temperature, density and composition with position. However, I hope that I have given you some idea about how it works to produce the colours we see.

Clouds and shadows

A weather forecaster will usually present the prospect of clouds with a tone that suggests slight distaste and fear that their audience will greet the news with disappointment. If the resulting weather is a grey overcast, such feelings are probably quite justified. However, clouds can be spectacular (Figure 13).

Figure 14. An image of the very start of the total solar eclipse from the La Silla site of the European Southern Observatory in the Atacama Desert in Chile on 2 July 2019. The 'Diamond Ring Sun' indicates that this viewpoint is right at the edge of the shadow cast by the Moon on the Earth. On the left side we see the very distant illuminated horizon through a long shadowed path of extinction resulting in a deep orange horizon. On the extreme right however, we view a white horizon along a path which, apart from the foreground, is illuminated by sunlight which produces the additional blue haze that is responsible for the aerial perspective. Note the similarities with the thundercloud image in Figure 13. ***Image credit: Raquel Shida, https://www.flickr.com/photos/raysinthesky/48416978517/***

How are they illuminated and how do they appear with such great variety? This is not the place to write a treatise on clouds, but I will try to introduce some ideas about how they are lit and how they can influence the appearance of the sky.

What is different between clouds and clear air? Clouds contain droplets of water and/or crystals of ice in addition to gas molecules and aerosols. These droplets and crystals are generally much bigger than molecules and most aerosols, and this means that they scatter light differently. As their sizes approach that of visible wavelengths, their ability to scatter strengthens and and depends much less on the colour of the light so that they usually appear white or grey.

As the light enters the cloud, it scatters from droplet to droplet (or crystal). Sometimes it is absorbed and heats the cloud, but often it emerges into clear air where it escapes into space, enters another cloud or hits the ground. Consequently, not all of the light entering or emerging from a cloud comes directly from the Sun, The cloud can also 'see' the clear sky, other clouds and the ground and, under many circumstances, these sources of illumination are important: see Figure 13 again — here the cloud sees the ground which is largely vegetated. Light from the orange sunlit horizon illuminates the lower rim of the belt of cloud around the storm. It can also be illuminated by flashes of lightning! We see all of these sources reflected from the underside of the cloud.

The other thing that a cloud does is to cast a shadow. This affects not only the ground but also the atmosphere under the cloud and has the effect of removing most of the blue haze of the aerial perspective that so influences the appearance of distant, sunlit landscapes. We see this effect under the thundercloud as the colour of the distant sunlight-illuminated horizon which appears orange because of the extinction experienced by the light from the distant sunlit clouds. Without the cloud shadow, the horizon would show a white sky and/or hazy blue mountains.

Another dramatic example of the shadow effect can be seen in the picture of the total solar eclipse shown in Figure 14. In this case, most obvious shadow is cast not by a cloud but by the Moon onto the atmosphere during the total solar eclipse over the La Silla site of the European Southern Observatory (ESO) in the Atacama desert in Chile. The 'Diamond Ring' stage of the eclipse indicates that the picture is taken from the very edge of the Moon's shadow on the ground. The right-hand horizon appears white due to aerial perspective while the left-hand part shows a deep orange horizon without the intervening blue haze. This is a lovely illustration of the 'twilight' colours which, due to the relatively high altitude of the Sun above the horizon, are relatively free of the effects of ozone absorption.

Lunar Eclipses and exo-planet transits

While a lunar eclipse in not bright enough to 'paint the sky' for us, it does paint the lunar surface in a way that echoes the mechanisms we have been discussing here. These eclipses are of especial interest as the configuration of the relevant bodies in space is analogous to those during observations of the transit of an exo-planet across the face of its parent star.

Figure 15 shows a dramatic sequence of lunar images taken during the eclipse of January 2019. The bottom left shows the deep blood-red illumination reaching the Moon from within the umbra of the Earth's shadow where the small amount of sunlight will have travelled through the lowest part of the atmosphere where it suffers an extinction which is

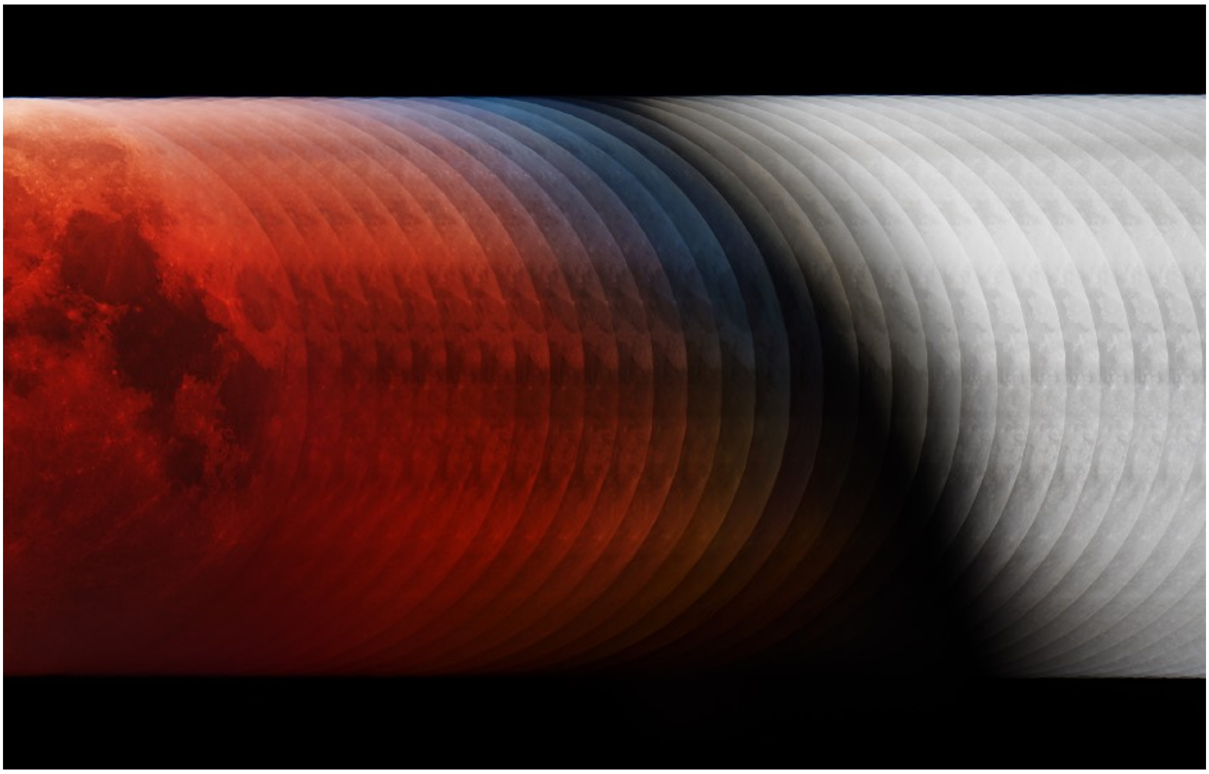

Figure 15. "Into The Shadow" by László Francsics. A stunning series of images taken during the lunar eclipse of 21 January 2019. Following the careful adjustment of the brightness by the photographer, this shows the colour produced by the extinction of a long tangential path of sunlight through Earth's atmosphere as the Moon emerges from the Earth's shadow. The path traverses successively high layers of the atmosphere until it passes through just the ozone layer and higher levels. The result is a beautiful ozone-blue. This is hard to see clearly with the eye as the blue chord of the image is much brighter than the 'blood-red' part of the Moon. ***Image credit: László Francsics , Astronomy Photographer of the Year 2019***

approximately twice that of a sunset seen from the ground. Near the top middle part of the image, the light reaching the Moon has travelled tangentially through the ozone layer which acts as a deep blue filter to produce a colour like that seen in the liquid ozone in Figure 4. At this altitude in the atmosphere there are few aerosols and so the path is very transparent except within the orange Chappuis absorption of the ozone which results in a blue with a slight purple tint, which is the character of 'The Blue Hour' at twilight. The photographer very skilfully employed 'High Dynamic Range' (HDR) imaging techniques to capture the lovely tonal range of the phenomenon which is difficult to perceive with the naked eye due to the large differential brightness across the lunar disk.

The geometrical configuration of the three bodies involved in an eclipse is shown in Figure 16. If we imagine the Sun being a star in another stellar system, with an exoplanet taking the place of Earth within it, and we exchange the Moon in Figure 16 with our Earth,

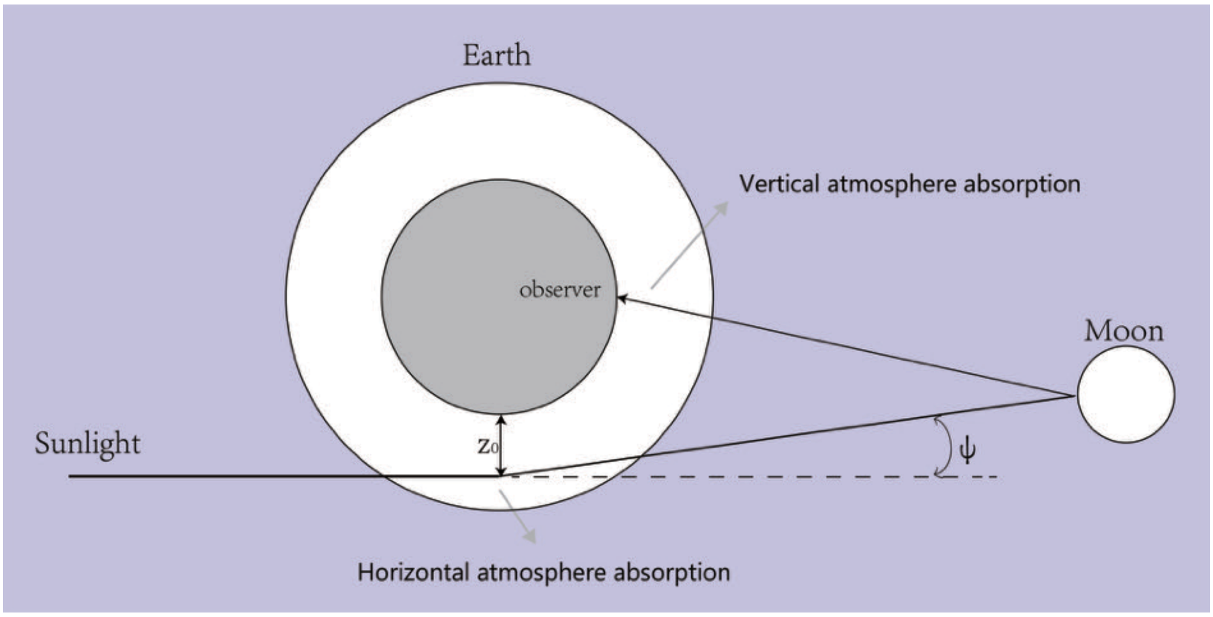

Figure 16. Schematic of a lunar eclipse (not to scale). This shows the geometry of an eclipse where the Earth passes between the Sun and the Moon. As sunlight enters the Earth's atmosphere from the left, it gets bent slightly inwards by atmospheric refraction and then illuminates the shadowed Moon. On this long tangential path through the atmosphere, the sunlight experiences twice the amount of extinction seen at sunrise or sunset seen from the ground, and it is this reddish light that faintly illuminates the Moon. As the Moon moves out of the umbral shadow, the light path traverses successively high layers of the atmosphere until it passes through just the the ozone layer which results in the subtle and unexpected blue hues on the Moon's surface seen in Figure 15. ***Figure credit: Figure 2. from Yan et al., International Journal of Astrobiology 14 (2): 255–266 (2015)***

now a very long way away, our telescopes can observe the distant star with a tiny dot passing across its disk. The relative sizes and scales have changed but the configuration is similar. The transit will appear as a slight decrease in the star's brightness as seen by us. For an earth-like planet around a sun-like star, this change in brightness is very small, but already we can detect and measure such events with some precision. Thousands of exoplanets, most of them bigger than Earth, have been discovered in this way.

What happens to the light during such a transit? If the planet has an atmosphere, some of the light reaching us will have passed through it on the way and the light reaching our telescope will carry the imprint of the absorption spectrum of the gases within it. Can we extract the 'telluric' spectrum of the exoplanet atmosphere from this signal? The answers is yes, and it has frequently been done for planets that are significantly bigger than Earth. To do it for smaller planets will need bigger telescopes in space and on the ground and these are already being built. There are different ways of making such measurements but the way to

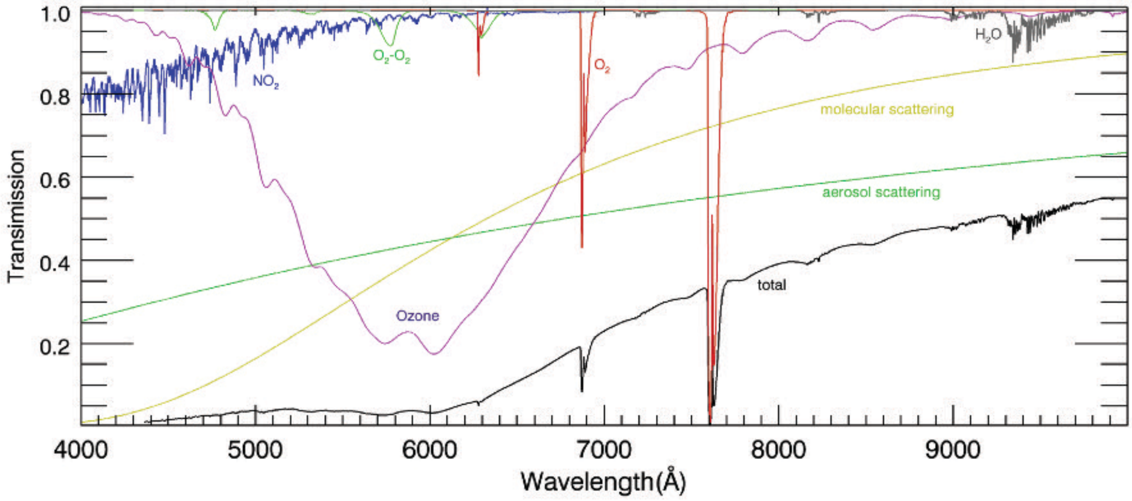

Figure 17. Models fitted to the high resolution spectral observations made of the lunar eclipse of 10 December 2011. These show the principal scattering and absorption contributors to the extinction of sunlight reflecting from the Moon after a long passage through the Earth's atmosphere. This is analogous to the process that is used to analyse the spectroscopic observations of transiting eco-planets. The principal extinction components are aerosol and molecular scattering and water, nitrogen dioxide and three forms of oxygen absorption (O_2, O_3 and O_4). Note the very strong influence of ozone (O_3) on the colour of the eclipsed Moon. ***Figure credit: Figure 7. from "High-resolution transmission spectrum of the Earth's atmosphere-seeing Earth as an exoplanet using a lunar eclipse", F. Yan, R. A. E. Fosbury, M. G. Petr-Gotzens, G. Zhao, W. Wang, L. Wang, Y. Liu and E. Pallé. International Journal of Astrobiology 14 (2): 255–266 (2015)***

imagine it is to look at the exaggerated thickness of the atmosphere in Figure 16. If you were looking at this planet transiting the face of a star, the planet itself would be a black shadow and the atmosphere might be transparent for the colour of light that you were measuring. If, however, a gas in the atmosphere absorbed light at that wavelength, the atmosphere would be more opaque and the planet would appear effectively larger and obstruct more light. So all we have to do, for each wavelength in the spectrum, is to measure the amount of obstructed light and interpret that as the 'effective radius' of the planet that is causing the obstruction. How that effective radius changes with wavelength can be expressed as the absorption spectrum of the atmosphere. From that, hey presto, we identify the presence of the different gases in the atmosphere and, perhaps, ask if life has been responsible for making the mix the way it is.

It sounds quite straightforward but, as you can imagine, it is not so easy in practice. It needs very high precision measurements and very stable conditions that are extremely challenging to achieve. It has been done however, and we are getting better at it.

A way to hone the techniques is to study lunar eclipses and try to measure the constituents of the Earth's atmosphere by observing its spectrum in the faint light reflected from the surface of the Moon. There is much more light available and the Earth casts a large shadow on the Moon that we are using as part of our transit telescope. This makes it much easier to do and we learn things from this that will help to design future measurements with the new telescopes. Figure 17 shows the result of such measurements, made during the lunar eclipse of December 2011 from near Beijing in China. For this eclipse, the grazing path of sunlight illuminating the Moon passed over the coast of Antarctica south of Australia. These observations were processed by forming the ratio of the light reflected from the Moon's surface during the eclipse to the fully illuminated Moon at the same spot on the surface after the eclipse was over. This means that the spectrum of the Sun and also the imprint of the Earth's extinction along the path from the Moon to the telescope cancel out, leaving the pure transmission spectrum resulting from the long horizontal atmospheric path over Antarctica.

This is represented by the black line spectrum at the bottom of the plot in Figure 17. The extinction models fits for the different components of extinction appear as the coloured spectra and these include molecular (Rayleigh) and aerosol scattering and water, nitrogen dioxide and three forms of oxygen absorptions (O_2, O_3 and O_4). Note that the dominant absorber is ozone (O_3) which has a large effect on both the blue and the red colours of the eclipsed Moon: this may come as a surprise! Another surprise is the strength of the nitrogen dioxide (NO_2) absorption (the blue spectrum at the top left) which is normally considered to be a pollutant that one might not expect over the Antarctic coast. We are not sure what causes it but there are three possibilities to be considered: emissions from cruise ships steaming along the coast in spring, the result of nitrogen fixation over the surface of Mount Erebus which has a permanent molten lava lake at its summit and is close to the light-path or, possibly, a product resulting from the production of nitrous oxide by bacteria emerging on the Antarctic ice in spring.

Painting the night sky

After the twilight fades, the Sun leaves its memory in the atmosphere as the airglow mainly visible above our heads. It is difficult to see with the eye but nonetheless can be impressive and

Figure 18. ESO's Paranal observatory in the northern Atacama Desert showing the airglow phenomenon along the horizon. Both the red and the green glow come from excited oxygen atoms slowly releasing the energy accumulated from ultraviolet sunlight during the daytime. The airglow can be seen by eye from a dark site with no Moon. However, it is too faint to trigger your cone receptors that give colour vision and you have to rely on the monochromatic rods to reveal it. Modern cameras however, are sensitive enough to reveal its full splendour. ***Photo credit: Y. Beletsky (LCO)/ESO***

colourful in long exposure photographs. Some of the most spectacular pictures of the 'airglow' have been taken from ESO's observatories in the Atacama Desert in Chile by a band of expert 'Photo-Ambassadors' using modern digital cameras (see, eg. https://www.eso.org/public/images/?search=Airglow). One of the images appears in Figure 18 where the scene is some sixty million times fainter than during a clear sunny day. In conditions like this, the human eye has to rely on its rod photoreceptors which do not produce a colour signal. To see the reds and greens requires the sensitivity of the modern camera.

The airglow results from atoms and molecules that have been excited by the ultraviolet radiation from the Sun during the day but retain a reservoir of energy that can be released slowly during the following night. The phenomenon has some similarities to that of the auroræ, indeed the green and red colours come from the same pair of oxygen transitions, but the excitation and emission mechanisms differ. The auroræ are excited by energetic particles from the Sun being guided by the Earth's magnetic field to release their light close to the magnetic poles. In contrast, the airglow is excited mainly by interactions with oxygen atoms that were produced during the day by UV photons from the Sun splitting oxygen molecules into their two atomic components. This happens high in the atmosphere, ~100km and above, and these atoms find it hard to reconnect and combine and so remain as singles into the night when they can interact with other atoms and molecules to release their red and green light. The predominant emissions both come from oxygen atoms in two colours, green at 558nm and a pair in the red at 630 and 636 nm. In order to emit red light, an oxygen atom must remain undisturbed by collisions for longer than it needs to emit the green light (from a different transition) and so the red glow is seen extending to much higher altitudes, where the density very low, reaching as high as the international space station ISS. The glows are highly variable and make patterns that drift across the sky with the red usually being brightest shortly after sunset. There are other contributors to the airglow but they are less apparent to the eye.

Final remarks

This article was written by a scientist with a hope that it might be of some interest to artists who wish for a more physical understanding of what they see around them in the natural world. I like to think that Turner did indeed wish to understand what he was painting with such great artistic insight. Later in his century, the impressionists did get the message and start looking carefully at what was there in front of them, even learning to paint shadows as blue under the blue sky that was illuminating them! I, for one, do not think that "unweaving the rainbow" detracts from its beauty, quite the opposite!

This article is based on a talk that was given first to the Daylight Academy on 24 August 2020 (https://www.youtube.com/watch?v=ZerHv6WY_ss&feature=youtu.be) and then to the Herschel Society on the 6th November 2020 (https://www.youtube.com/watch?v=P9v9pFluF-M&t=4329s). I should like to thank the organisers of these events, Manuel Spitschan and Anthony Symes, for arranging them and stimulating me to work on this topic. I am grateful to the photographers, mentioned in the credits both in this article and in the talks, who kindly allowed me to use their excellent work to illustrate this work. I especially thank David Malin who kindly made many perceptive comments which improved the clarity of the article.

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