Blue Flame and Green Comet

being a spectral analysis of comet vapor, expounding on its relation to a commonly observed phenomenon on Earth

Glenn Davis `<gdavis@gluonics.com>`

September 20, 2024

Introduction

In March, Judy sent me an article [Bennet, 2016] about Comet 252P/LINEAR - a green comet passing close to earth. Green is not a common color in astronomy so I decided to investigate. The green color comes from diatomic carbon vapor - C_2 - and its *Swan bands*. These wavelength bands (about 5 major ones) were discovered in a Bunsen burner flame by Scottish physicist William Swan [Swan, William, 1857], who wrote:

> While in the ordinary flames of coal gas and oil, solid carbon is separated, it is well known that by burning a mixture of gas and air, the separation of carbon may be entirely prevented, and a smokeless flame obtained. My attention was at first accidentally directed to the subject of this paper while using a species of gas lamp in which this object is effected in a very simple manner. As this lamp - the invention of Professor BUNSEN of Heidelberg - has only lately been introduced into this country, and as I have made extensive use of it in my experiments, it may be proper to explain its construction.

Swan thought that the the source of the bands was hydrocarbon molecules. After seven decades of controversy, it was definitively determined that the source of these bands was actually diatomic carbon [Pretty, 1927]. The color of a blue butane flame is a mixture of the colors from hydrocarbons and diatomic carbon. I thought it would be interesting to separate the light from hydrocarbons and the light from diatomic carbon and to display both colors accurately.

```
library( colorSpec )
library( spacesRGB )      # for function plotPatchesRGB()
```

Featured functions in this vignette are: `chop()` and `bind()`.

The Flame

I found this spectrum of the blue part of a butane flame in a Wikipedia article [Wikipedia, 2015] on the Swan bands:
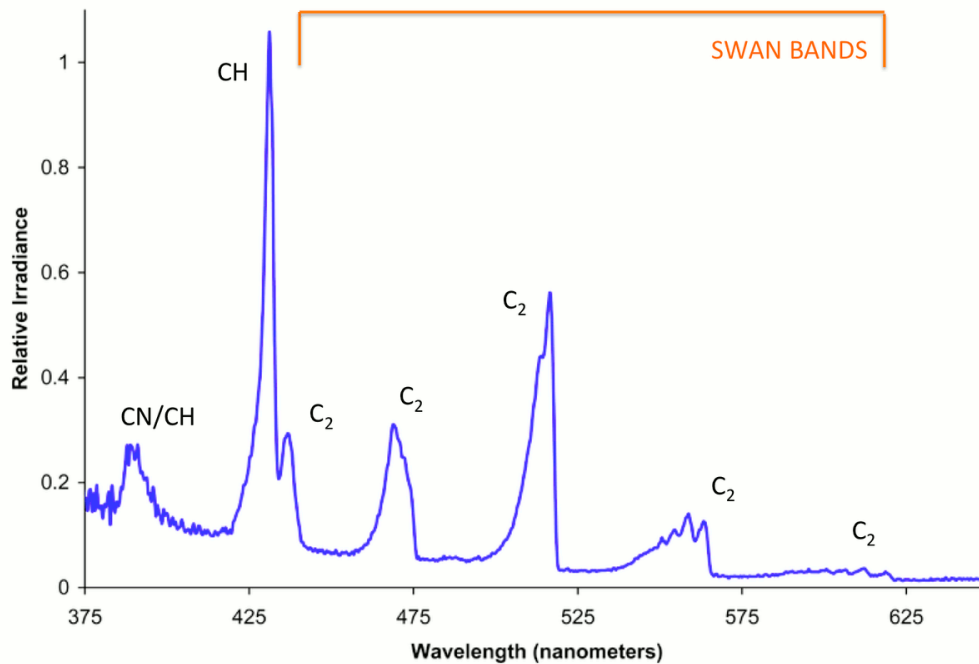
Figure 1. The spectrum of a blue flame

Note that there is a dividing point at about 435 nm. Below this point the spectrum is from CH (carbyne) and above this point the spectrum is from C_2. Fortunately user Deglr6328 also posted the numerical data, which is included in this package as `BlueFlame.txt`. Here is the same data as plotted using **R**.

```
path = system.file( "extdata/sources/BlueFlame.txt", package="colorSpec" )
blueflame = readSpectra( path, seq(375,650,0.5) )
par( omi=c(0,0,0,0), mai=c(0.6,0.7,0.3,0.2) )
plot( blueflame )
```
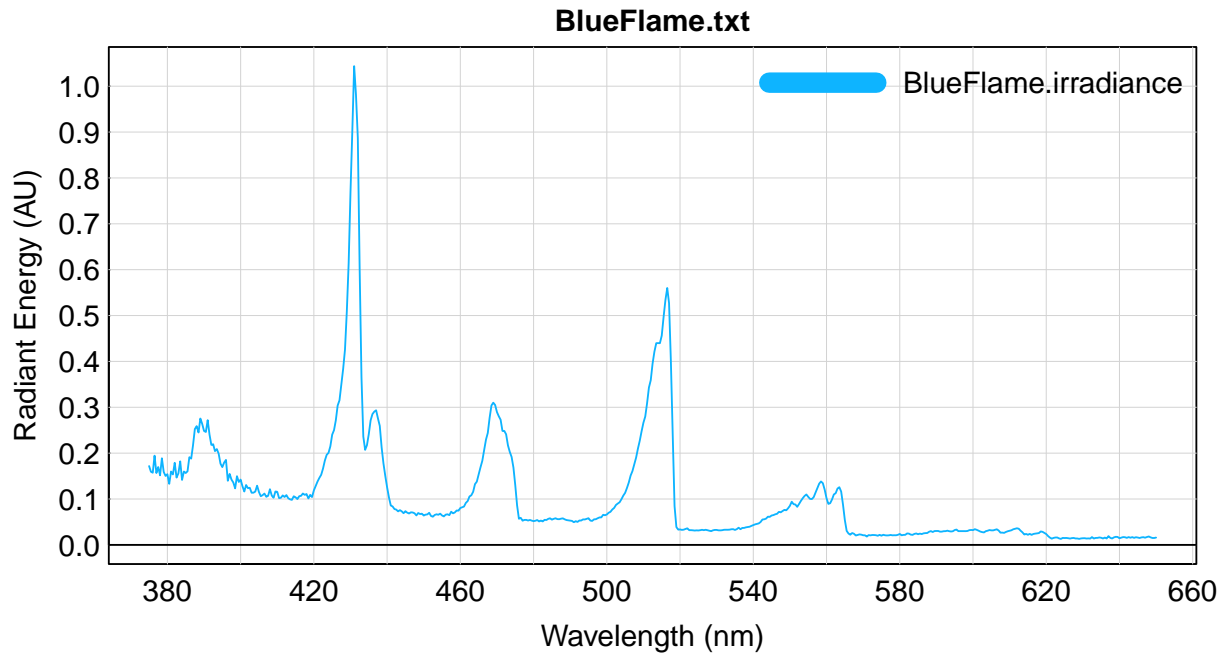
BlueFlame.txt

Figure 2: The spectrum of a blue flame

The flame color you see here is accurate on a display calibrated for sRGB [Wikipedia, 2013].

Splitting the Flame

Here is a simple split into low and high parts:

```
flame.split = chop( blueflame, interval=c(432,435), adj=0.8 )
combo = bind(flame.split,blueflame)
par( omi=c(0,0,0,0), mai=c(0.6,0.7,0.3,0.2) )
plot( combo, subset=c(T,T,F) )
```
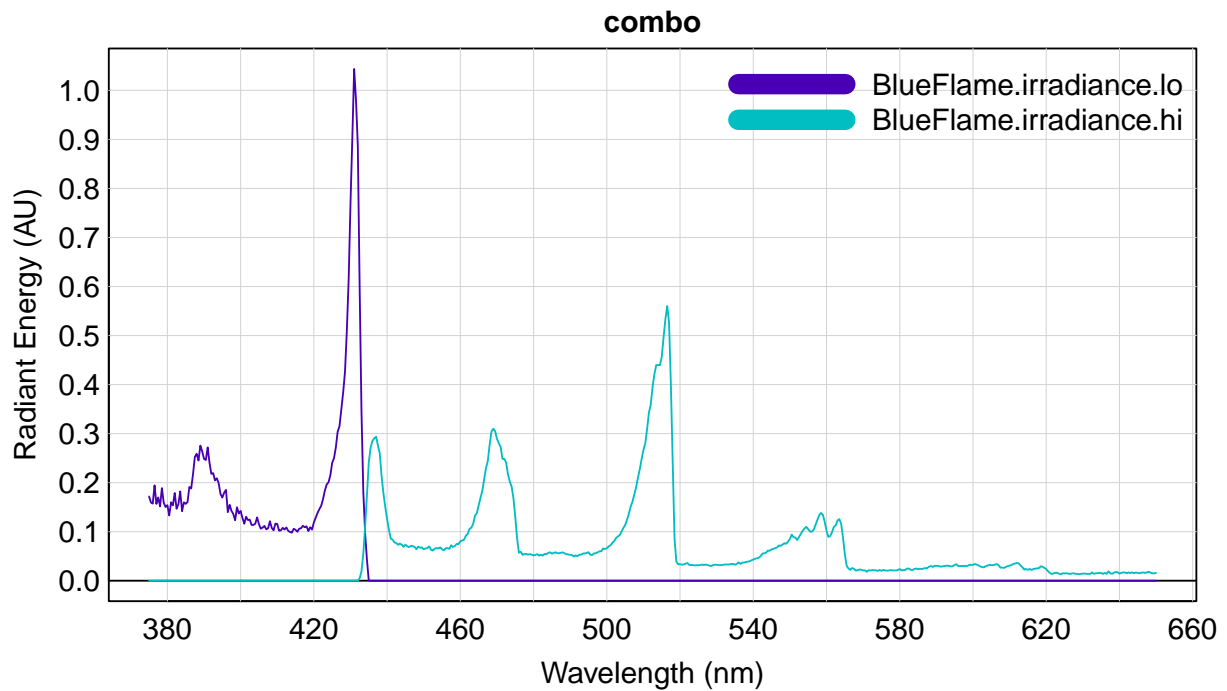
Figure 3: The sum of the low and high parts is the original spectrum

Note that the Swan bands, in the high part on the right, are a bluish-green. The CH bands, in the low part on the left, are violet. Here is a zoomed-in plot at the splitting interval (432 to 435 nm):

```
par( omi=c(0,0,0,0), mai=c(0.6,0.7,0.3,0.2) )
plot( combo, subset=c(T,T,F), xlim=c(430,440) )
```
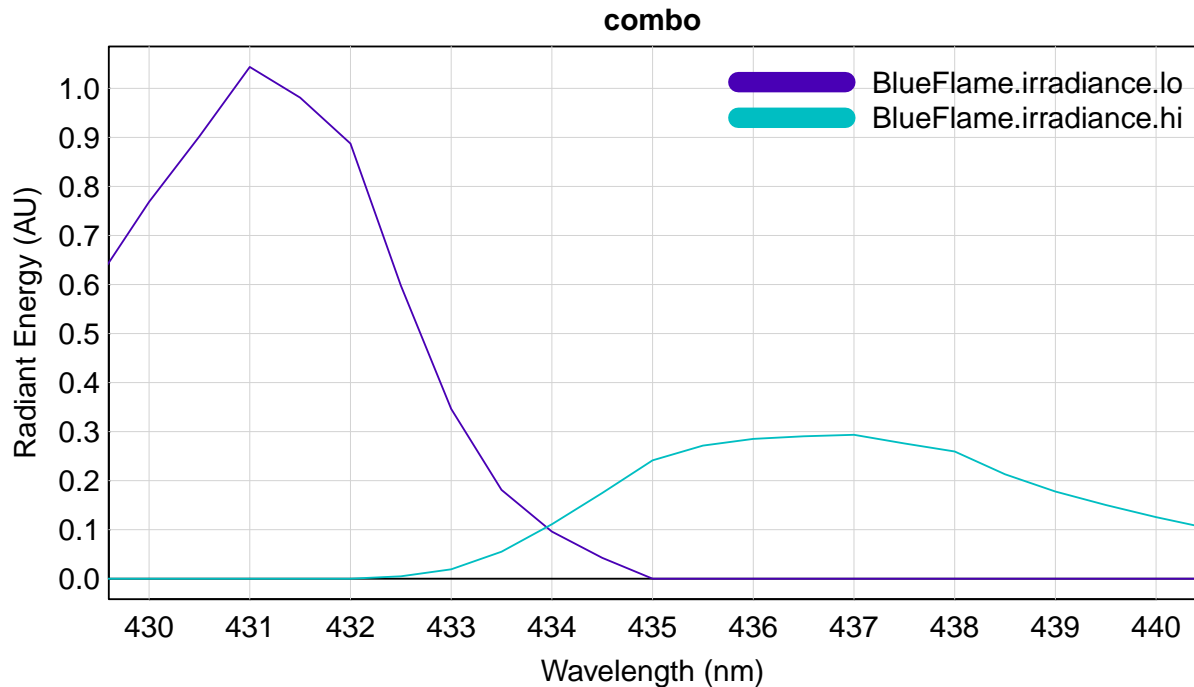
Figure 4: The sum of the low and high parts is the original spectrum

The 2 colors you see here are fairly accurate on a display calibrated for sRGB, except that both are too vivid for sRGB and so they have been clippped. The sum of these 2 colors is (approximately) equal to the color in Figure 2. Later these will be displayed as large patches.

The Atmosphere

But wait a minute ! This blue-green color is what would be viewed from the neighborhood of the comet in space. We are viewing it through the atmosphere, and we know that the molecules of air scatter blue light (short wavelength) more than green light (middle wavelength), through Rayleigh scattering. So the comet should appear a little greener from the surface of the earth than from space. Fortunately there is a standard, [ASTM, 2003], for the typical transmittance of the atmosphere:

```r
par( omi=c(0,0,0,0), mai=c(0.6,0.7,0.3,0.2) )
plot( atmosphere2003, xlim=c(375,650), ylim=c(0,1), col='black' )
```
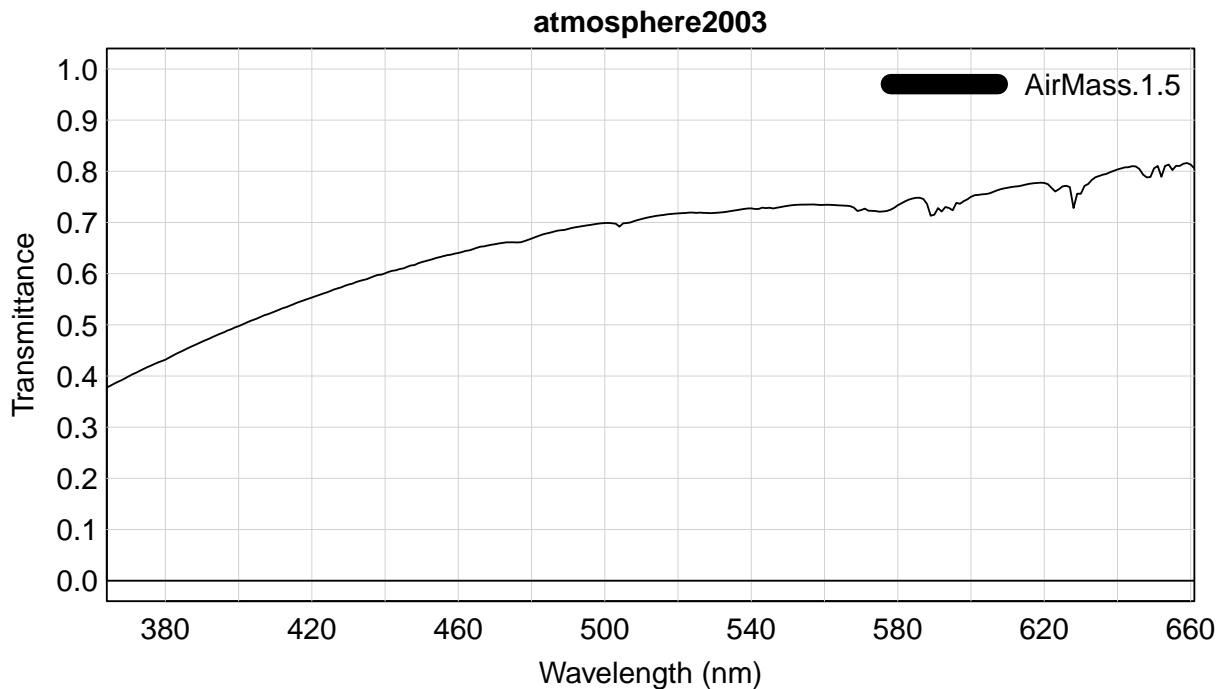
Figure 5: The transmittance of the atmosphere, for an Air Mass of 1.5

So the blue region is attenuated more than the green region. An *Air Mass* of 1.5 means that the optical path length of the light is 1.5 times what it is at the zenith. This means that the comet is being viewed at about 48° from the zenith. I could not find any data on the transmittance at the zenith itself. The insignificant dips in the transmittance spectrum are due to molecular absorption (probably water vapor) and not scattering.

And here is the effect of the atmosphere on the Swan bands:

```
atmosphere = resample(atmosphere2003,wavelength(blueflame))
swan.atmo  = product( subset(flame.split,2), atmosphere )
specnames(swan.atmo) = "Swan bands, as viewed through the atmosphere"
combo = bind( blueflame, flame.split, swan.atmo )
specnames(combo) = c( "blue flame",
                      "CH part of blue flame", "Swan bands, as viewed in space",
                      "Swan bands, as viewed through the atmosphere")
par( omi=c(0,0,0,0), mai=c(0.6,0.7,0.3,0.2) )
plot( combo, xlim=c(375,650), ylim=c(0,0.7), subset=3:4 )
```
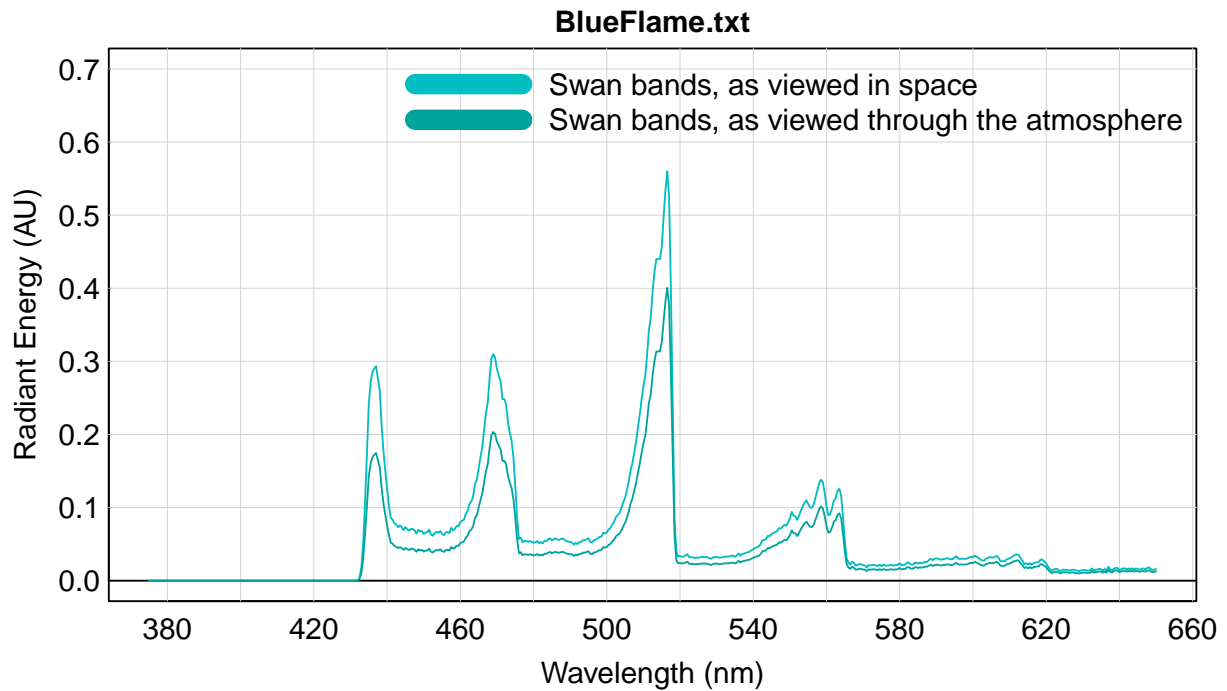
BlueFlame.txt

Figure 6: The transmittance of the atmosphere, for an Air Mass of 1.5

The second color is definitely greener than the first, and the next section will show this even better.

Colored Patches for an sRGB Display

Here we collect the colors discussed above and display them as large rectangular patches.

```
RGB = product( combo, BT.709.RGB, wavelength='auto' )  # linear scene sRGB
RGB = RGB/max(RGB)   # normalize so the maximum value is 1
par( omi=c(0,0,0,0), mai=c(0.2,0.2,0.2,0.2) )
plotPatchesRGB( RGB, space='sRGB', which='scene', labels='right', adj=c(0,NA) )
```
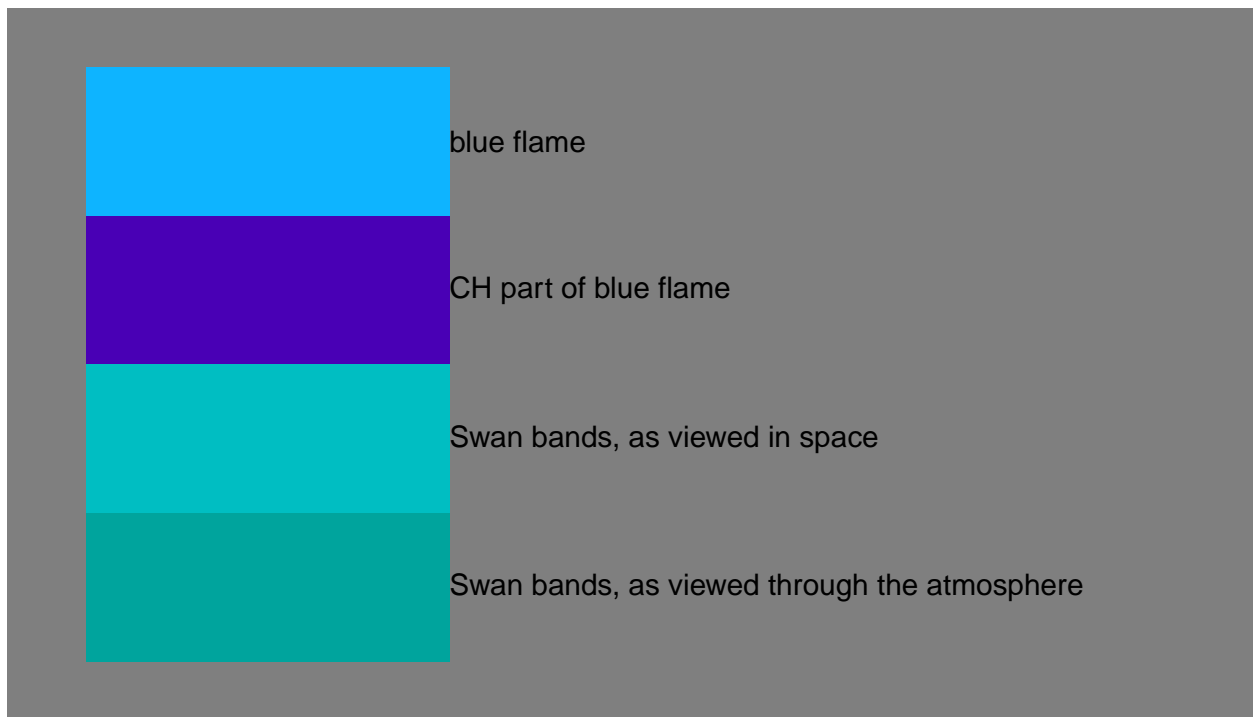
Figure 7: Colors as patches - computed for an sRGB display

In this figure:

color(blue flame) = color(CH part of blue flame) + color(Swan bands, as viewed in space)

The object `BT.709.RGB` is a built-in hypothetical camera. Except for the blue flame itself, the colors are slightly outside the sRGB gamut. For this reason they are slightly inaccurate when viewed on a display calibrated to sRGB, but see the next section.

Colored Patches for an Adobe RGB Display

Wide-gamut displays are not that common, but are becoming more so. Most of them can be calibrated to the Adobe RGB color space [Wikipedia, 2016], which is probably the most popular wide-gamut RGB space. Here are the same large patches as in the previous section, but computed for Adobe RGB.

```
RGB = product( combo, Adobe.RGB, wavelength='auto' ) # linear scene Adobe RGB
RGB = RGB/max(RGB)  # normalize so the maximum value is 1
par( omi=c(0,0,0,0), mai=c(0.2,0.2,0.2,0.2) )
plotPatchesRGB( RGB, space='AdobeRGB', which='scene', labels='right', adj=c(0,NA) )
```

blue flame

CH part of blue flame

Swan bands, as viewed in space

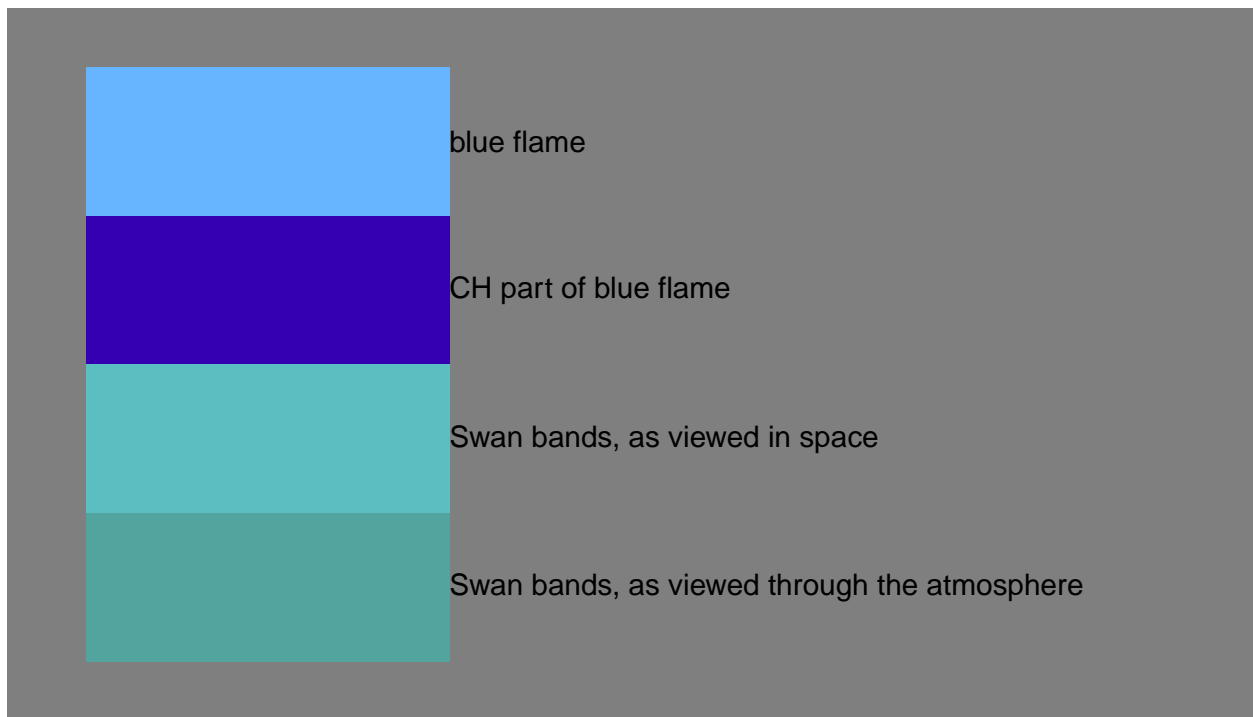Swan bands, as viewed through the atmosphere

Figure 8: Colors as patches - computed for an Adobe RGB display

This figure is best viewed on a display calibrated for Adobe RGB. The "CH part of blue flame" is still too vivid (the green is negative) but the other 3 colors are in the Adobe RGB gamut. Figure 9 is a diagram comparing the 2 color spaces.
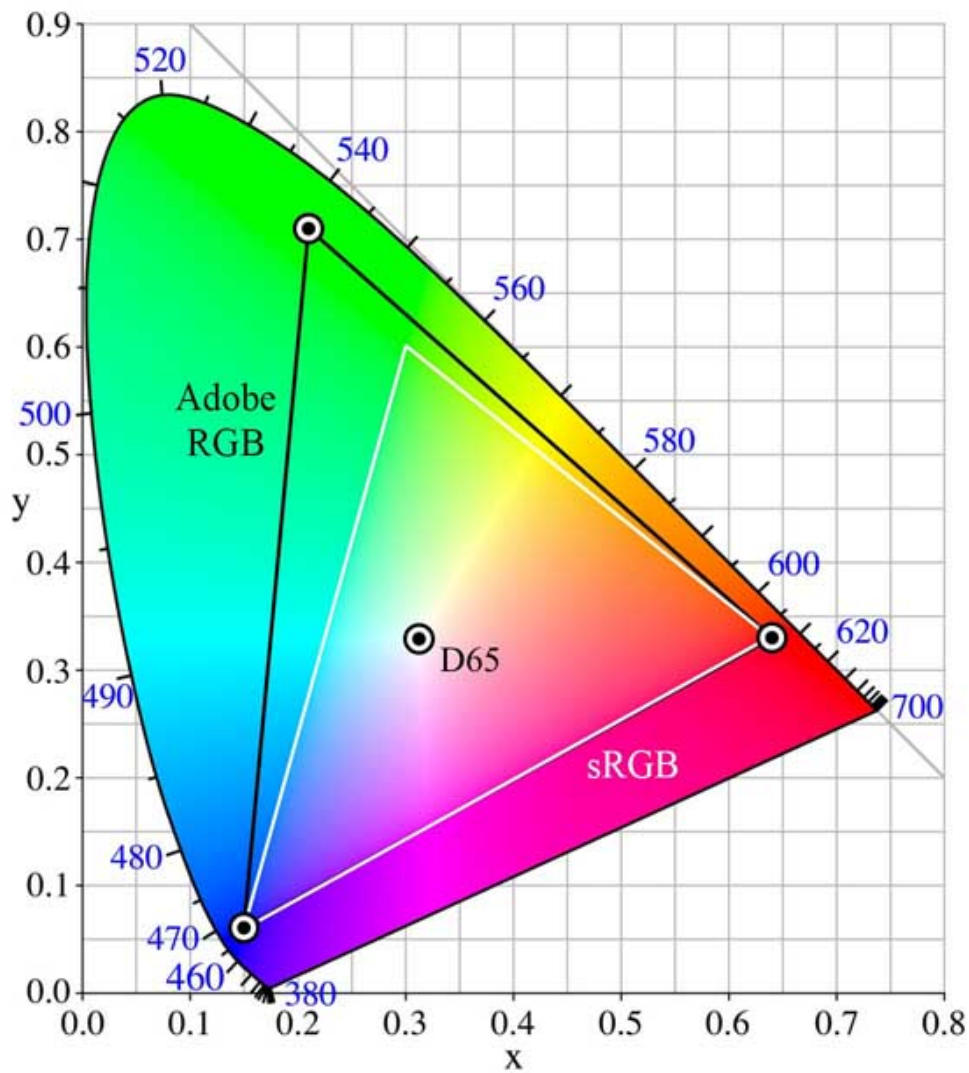
Figure 9. A comparison of the Adobe RGB (1998) and sRGB chromaticity gamuts within the CIE 1931 xy chromaticity diagram; taken from [Wikipedia, 2016]. The sRGB gamut is lacking in cyan-green hues.

Further Analysis

Of course, real comet vapor has many more molecules than diatomic carbon. A better analysis of comet color would include those chemical spectra in the mix. Also notice that the blue flame spectrum has a positive baseline, so a better analysis would find the source(s) of this baseline and possibly subtract it.

References

[ASTM, 2003] ASTM (2003). ASTM G173-03. Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface. *ASTM Subcommittee G03.09 on Radiometry.*

[Bennet, 2016] Bennet, J. (Mar 21, 2016). Watch a Big Green Comet And Its Twin Fly Past the Earth. *Popular Mechanics.* https://www.popularmechanics.com/space/telescopes/a20022/large-green-comet-twin-will-fly-close-to-earth.

[Pretty, 1927] Pretty, W. E. (1927). The Swan Band Spectrum of Carbon. *Proceedings of the Physical Society*, 40(1):71.

[Swan, William, 1857] Swan, William (1857). On the Prismatic Spectra of the Flames of Compounds of Carbon and Hydrogen. *Transactions of the Royal Society of Edinburgh*, 21:411–430.

[Wikipedia, 2013] Wikipedia (2013). sRGB — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/wiki/SRGB [Online; accessed April-2016].

[Wikipedia, 2015] Wikipedia (2015). Swan band — Wikipedia, The Free Encyclopedia. Deglr6328 at English Wikipedia [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons [Online; accessed April-2016].

[Wikipedia, 2016] Wikipedia (2016). Adobe RGB — Wikipedia, The Free Encyclopedia. By Mbearnstein37 (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons. [Online; accessed April-2016].

Session Information

This document was prepared September 20, 2024   with the following configuration:

- R version 4.4.1 (2024-06-14), `x86_64-pc-linux-gnu`

- Running under: `Ubuntu 24.04.1 LTS`

- Matrix products: default

- BLAS: `/usr/lib/x86_64-linux-gnu/openblas-pthread/libblas.so.3`

- LAPACK: `/usr/lib/x86_64-linux-gnu/openblas-pthread/libopenblasp-r0.3.26.so` ; LAPACK version3.12.0

- Base packages: base, datasets, grDevices, graphics, methods, stats, utils

- Other packages: colorSpec 1.5-0, knitr 1.48, rmarkdown 2.28, spacesRGB 1.5-0

- Loaded via a namespace (and not attached): R6 2.5.1, bslib 0.8.0, buildtools 1.0.0, cachem 1.1.0, cli 3.6.3, compiler 4.4.1, digest 0.6.37, evaluate 1.0.0, fastmap 1.2.0, highr 0.11, htmltools 0.5.8.1, jquerylib 0.1.4, jsonlite 1.8.8, lifecycle 1.0.4, maketools 1.3.0, microbenchmark 1.5.0, rlang 1.1.4, sass 0.4.9, sys 3.4.2, tools 4.4.1, xfun 0.47, yaml 2.3.10