Blackbody Radiation: Measuring the Temperature of Stars

Our goal in this lab was to estimate the temperature of objects emitting radiation in the visible spectrum of light. We calculated intensity ratios for red, green, and blue light sensors from the DSLR Canon 70D camera we used to take pictures of a metal piece in a furnace, the sun, and several stars (see Figure 1 for setup diagrams). Under the assumption that the objects were ideal blackbodies, we used Matlab (see A-3 & A-4 for code) to calculate approximations for their temperatures. We then calibrated the image data using known temperatures to get more accurate and consistent temperatures that accounted for various factors of inaccuracy in our original temperature approximations. We observed the phenomena of blackbody radiation, atmospheric scattering, electromagnetic spectra, and also saw fascinating night sky objects at the Duke Observatory.

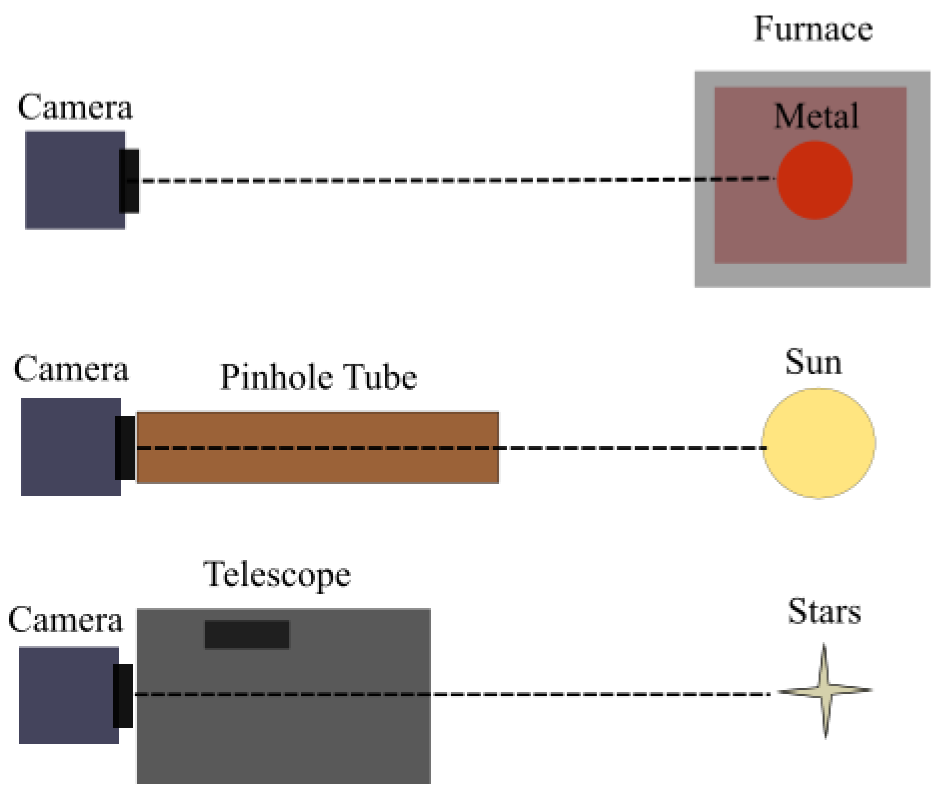

Figure 1. Schematic Diagram of the three setups used in this lab. The top shows the setup for the image metal piece, taken about one meter from the metal piece. The middle shows the setup for imaging the sun, for which Ryan connected a long tube with a small hole on the far end to the camera to reduce the intensity of the sun. The bottom shows the setup for collecting intensities for stars using the telescope at the Duke Observatory. The diagrams are obviously not to scale.

Metal Piece:

Our first objective in this lab was to measure the temperature of the metal and sun without calibration. We created a Matlab script, using some given code, to estimate the temperatures of the two objects. Using our code (see A-3), we calculated intensities for the red, green, and blue light collected by the camera for the region shown in Figure 2 by averaging the intensity over this region, and from these intensity values found the intensity ratios I_{green} / I_{red} , I_{blue} / I_{green} , and I_{blue} / I_{red} .

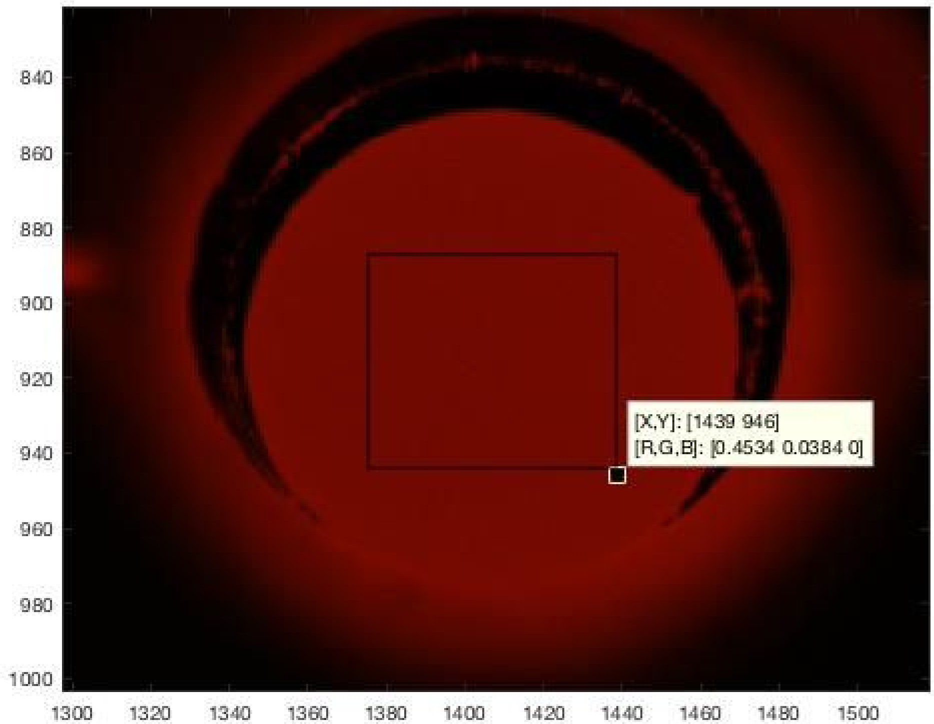

Figure 2. Representative image of the metal object in the furnace. The overlaid black rectangle shows the area of interest from which we took intensity data to calculate the intensity ratios discussed above. A similar rectangular selection was used for the image of the sun and stars, although it is much smaller and hard to select for the stars.

The measured intensity ratios for the metal piece were found to be:

$$\begin{aligned} I_{green} / I_{red} &= .5278 \\ I_{blue} / I_{green} &= .1987 \\ I_{blue} / I_{red} &= .1049 \end{aligned}$$

We then wrote a radiation intensity spectral density function that takes in wavelength and a range of temperatures. From this, and using the given transmission functions for the different camera filters, we calculated the expected or theoretical intensity ratios as a function of temperature (see Figure 3).

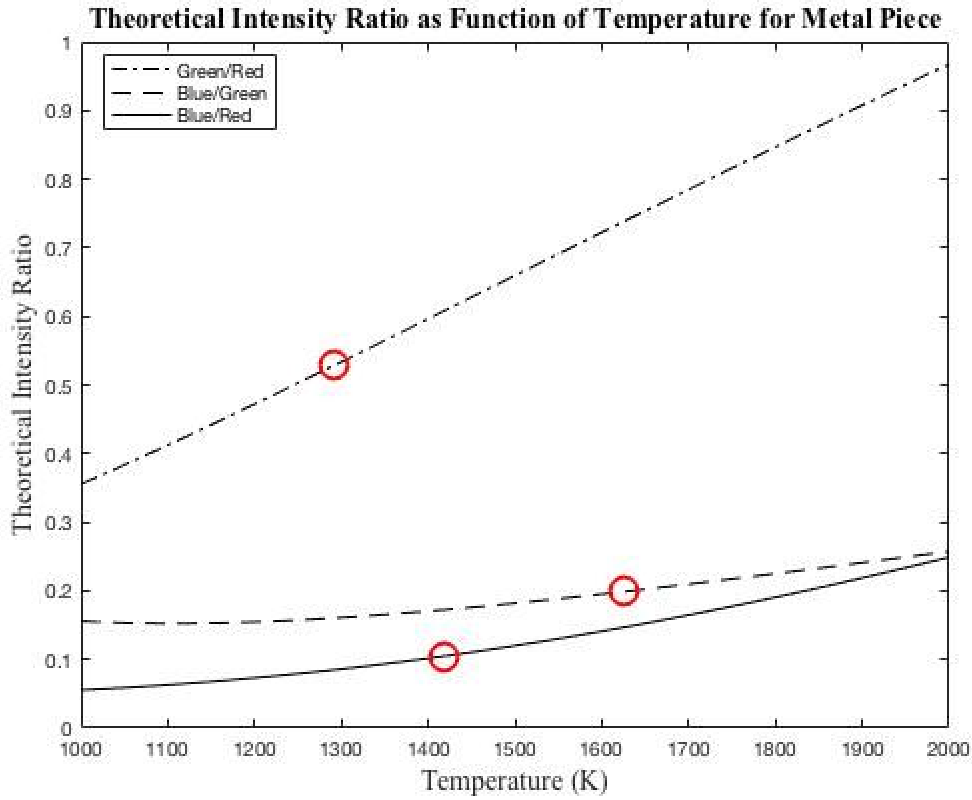

Figure 3. Representative plot of the three theoretical intensity ratio curves as a function of temperature for the $I_{green}(T) / I_{red}(T)$, $I_{blue}(T) / I_{green}(T)$, and $I_{blue}(T) / I_{red}(T)$ of the metal piece.

Using measured intensity ratios and the respective theoretical ratio curves seen in Figure 3, we calculated the temperature approximation for each intensity ratio using linear interpolation with the Matlab interp1 command. The resulting values for temperature were 1290 K for the green/red ratio, 1625 K for the blue/green ratio, and 1419 K for the blue/red ratio (see Table 1). The red circles on the plot in Figure 3 show these points with coordinates corresponding to the measured ratio and temperature approximation.

We conducted the above procedure under three assumptions: (i) that the object is an ideal blackbody, (ii) that the media between the camera and the object does not affect the filter spectra, and (iii) that the camera filters are perfectly calibrated. However, using these assumptions, we got different temperature approximations for each of the three intensity ratios. Thus, for the metal piece (and the Sun and stars), we need to account for some imperfection in some or all of the assumptions made by calibrating the transmission functions with the appropriate scaling factors.

For the metal piece, the assumption of ideal blackbody is fine because it does not reflect any radiation in the visible range of light. Furthermore, as the camera is only a meter away from the metal object, it is fine to neglect the impact the air has on the object, as moving the object twice as far away would not change its appearance in terms of the spectrum we would see. Thus, the likely cause of the inaccurate and inconsistent temperature approximations is that the camera is not perfectly calibrated. To calibrate for this, we found the theoretical intensity ratio corresponding to the known temperature of the metal (1373 K) for the green/red intensity ratio and the blue/green intensity ratio. We then calculated scaling factors by dividing the measured ratio by these calibrated ratios. The scaling factor for the green/red ratio was 0.911 and the factor for the blue/green ratio was 0.843. Treating the third constant as 1, we multiplied the corresponding transmission functions by these scaling factors (see scaling factors in A-2) and recomputed the intensities, ratios, and temperature approximations for the metal piece. The temperature estimate for each intensity ratio after this calibration was 1373 K (see Table 1).

Table 1. Temperature approximations for Metal before and after calibration (known temperature: 1373 K)

Calibration	Green/Red Temp. (K)	Blue/ Green Temp. (K)	Blue/Red Temp. (K)
None	1290	1625	1419
Metal	1373	1373	1373

This calibration was successful in approximating accurate and consistent temperatures, meaning we successfully accounted for the inaccuracy in the original intensity data reasonably assumed to be due to imperfect camera filter calibration.

Sun:

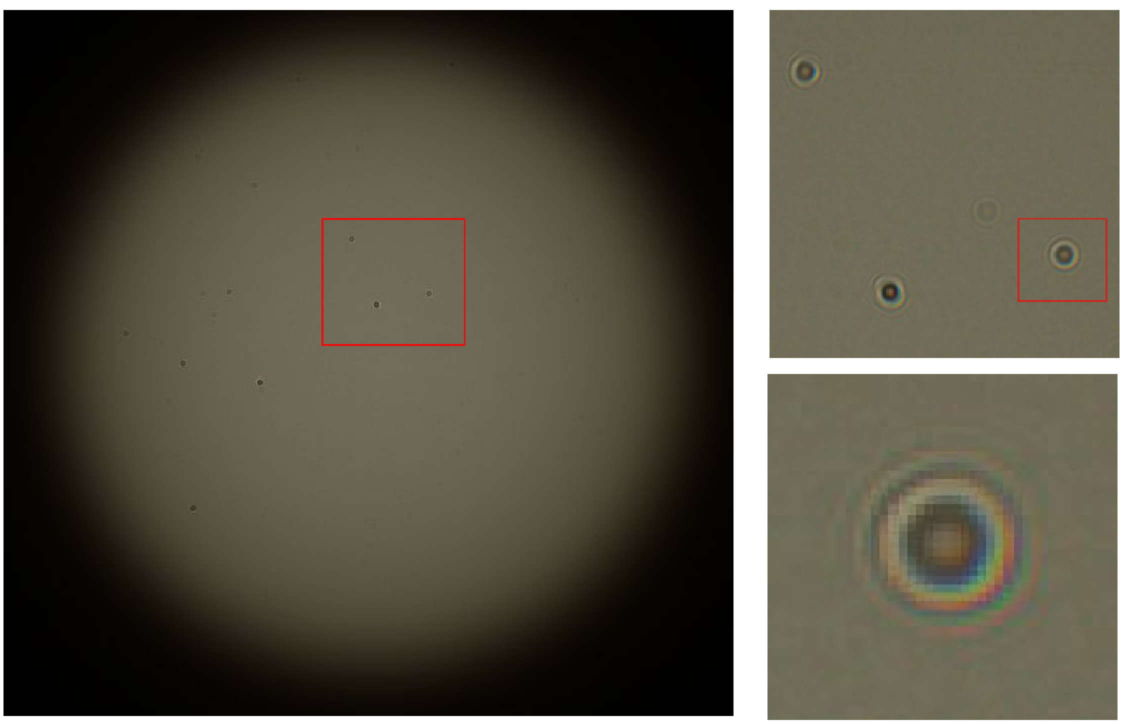

Figure 4. Image of the Sun used in the lab. Red boxes show area of zoom.

When analyzing the image of the sun for the lab (see Figure 4), we noticed what looked like, at a glance, sunspots. However after looking closer, we realized there were many small airy diffraction patterns spread across the image of the sun. It is our guess that these airy diffractions are the result of the bright light from the pinhole hitting suspended particles in the pinhole tube (see Figure 1 for setup of sun imaging). Although these patterns should not appear on the image of the sun, after selecting a region of interest that excluded the airy diffractions and recalculating the temperature approximations, we determined it did not significantly alter the results. So the airy patterns were ignored, although they are interesting to point out.

Once we had calibrated the transmission functions for the metal piece, we repeated the same pre-calibration process used for the metal piece to calculate the temperature approximations of the Sun. For the sun calculations however, we started with the calibrated transmission functions from the metal, so the camera filters would be perfectly calibrated. From these calculations, the temperature approximations for each intensity ratio were as follows: 5743 K for the green/red intensity ratio, 3840 K for the blue/green intensity ratio, and 4526 K for the blue/red intensity ratio (see Table 2).

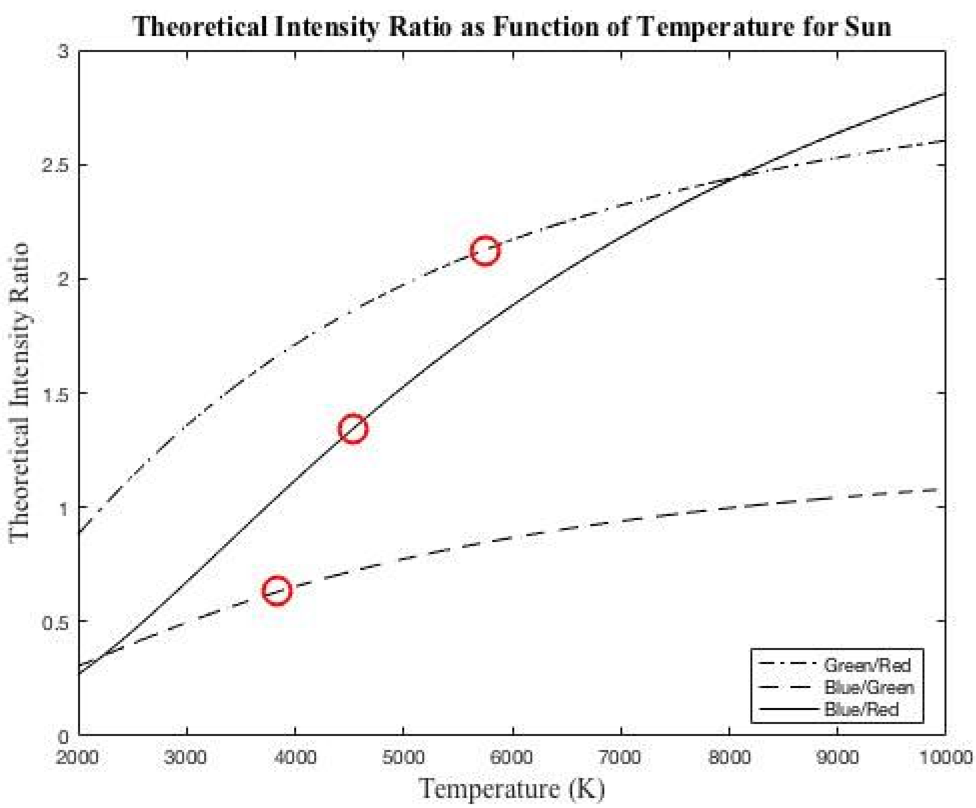

Figure 5. Representative plot of the three theoretical intensity ratio curves as a function of temperature for the $I_{green}(T) / I_{red}(T)$, $I_{blue}(T) / I_{green}(T)$, and $I_{blue}(T) / I_{red}(T)$ of the Sun. As in the representative plot for the metal piece in Figure 3, the red circles show the coordinates of the measured intensity ratio and corresponding temperature along the theoretical intensity ratio curve.

With the estimates for the Sun's temperature, the camera sensor transmissions are perfectly calibrated, and the Sun can be assumed to be an ideal blackbody. However, unlike for the metal piece, the atmosphere or media between the camera and the Sun affects the observed spectra of the Sun. We know that the atmosphere scatters blue light more than red light because when the Sun is low on the horizon, it appears much more red because the light travels through more atmosphere than when it is overhead. This uneven scattering is also why the sky appears blue. Keeping this in mind, we noticed the temperature approximation for the green/red intensity ratio is much closer to the known value for the temperature of the Sun (5778 K) than the other two estimates (see Table 2). This makes sense because green light is filtered less than blue light. It makes sense that the two ratios with blue intensity in the numerator would be further from the known value because blue light is filtered more. It also makes sense that the blue/red approximation is closer to the known value than the blue/green approximation because while green is filtered more than red, green and red are in the denominator, so the impact on the approximated temperature would be flipped.

Thus, we performed the same process used to calibrate the metal piece to calibrate the transmission functions for the Sun to account for atmospheric scattering. From this recalibration, the scaling factor to account for the atmospheric scattering for the green/red ratio was 0.997 and the factor for the blue/green ratio was 0.743 (see A-2). After applying these calibration scaling factors on top of the metal calibration factors, the temperature approximation for each of the three intensity ratios was 5778 K.

Table 2. Temperature approximations for Sun before and after calibration (known temperature: 5778 K)

Calibration	Green/Red Temp. (K)	Blue/ Green Temp. (K)	Blue/Red Temp. (K)
Metal	5743	3840	4526
Sun	5778	5778	5778

Thus, this calibration was successful in accounting for the factors, most likely atmospheric scattering, that were giving inconsistent approximations as we were able to calculate temperatures accurate and consistent with the known value.

Stars:

Now that we have calibrated the camera transmission functions to account both for the imperfect calibration of the camera sensors and for the effects of atmospheric scattering, we can calculate approximations for the temperatures of the stars we imaged through the telescope at the Duke Observatory. However, there is another factor altering the observed spectra of the stars we imaged that did not affect the spectra of the Sun. Interstellar clouds of dust and gas between the stars and our solar system filter blue light more than red light just as the Earth's atmosphere. It is difficult to account for this effect on the temperature approximations without knowing the temperature of an object with the same interfering clouds altering its spectra. Luckily, for binary stars, such as those seen in Figure 6, there are two stars experiencing the same cloud scattering effect. For all star images, binary and non-binary, the image and region of interest selected were chosen to avoid oversaturation in all of the color channels.

Figure 6. Binary stars Albireo (left) and Mizar (right).

For **Albireo**, using the calibration from the Sun image, the temperature of the brighter star (Albireo A) was 3881 K for the green/red ratio, 2728 K for the blue/green ratio, and 3168 K for the blue/red ratio. The known temperature of this star is 4270 K. The temperatures of the fainter star (Albireo B) were 8817 K for the green/red ratio, 4254 K for the blue/green ratio, and 5541 K for the blue/red ratio. The known temperature of this star is 13200 +/- 600 K. As with the Sun, the green/red ratio is closest to the known values, followed by the blue/red ratio and then the blue/green ratio (see Table 3). The reasoning for this is the same, although they are further from the known value because of the extra effect from the interstellar clouds. Using the known temperature of Albireo A, we recalibrated the system so that all three intensity ratios gave consistent values of 4270 K for Albireo A. The scaling factors for this recalibration can be seen in A-2. Using this calibration then for Albireo B, we found the temperature approximations to be 11420 K for the green/red ratio, 9426 K for the blue/green ratio, and 10223 K for the blue/red ratio. These values, calibrated for Albireo A, are closer to the known temperature of Albireo B of 13200 +/- 600 K than the uncalibrated temperatures. This recalibration was not completely successful at estimating Albireo B given Albireo A's temperature, but it was a major improvement over the uncalibrated sun transmission filter estimates, showing more consistency and accuracy to the known value of 13200 +/- 600 K (see Table 3 for comparison). Other factors influencing these approximations may be imperfect data collection and/or data analysis.

Table 3. Temperature approximations for Albireo B using known temperature of Albireo A (13200 K)

Calibration	Green/Red Temp. (K)	Blue/ Green Temp. (K)	Blue/Red Temp. (K)
Sun	8817	4254	5541
Albireo A	11420	9426	10223

The same process was repeated for the double star **Mizar**. The temperature of the brighter star (Mizar A) using the sun calibration was 9293K for the green/red ratio, 5654K for the blue/green ratio, and 6848K for the blue/red ratio. The temperature of the fainter star (Mizar B) using the sun calibration was 8027 K for the green/red ratio, 5554 K for the blue/green ratio, and 6446 K for the blue/red ratio (see Table 4). Using the known temperature of Mizar A (9000K +/- 200K), we recalibrated the Mizar system (see A-2 for recalibration scaling factors). We found the approximate temperatures of Mizar B after recalibration to be to be 7814K for the green/red ratio, 8736K for the blue/green ratio, and 8290K for the blue/red ratio. This calibration for Mizar was fairly successful because the approximated temperatures using the Mizar A calibration were more consistent and on the whole closer to the known value of 9000 K (see Table 4). We are not sure why the green/red temperature was lower than the other two ratios, this was not expected as the effect of an interstellar cloud would filter blue light more than green, but we wondered whether it could be due to the blue appearance of the star, as the same results occurred with Sirius, another blue star.

Table 4. Temperature approximations for Mizar B using known temperature of Mizar A

Calibration	Green/Red Temp. (K)	Blue/ Green Temp. (K)	Blue/Red Temp. (K)
Sun	8027	5554	6446
Mizar A	7814	8736	8290

Unfortunately, for non-binary stars, such as those seen in Figure 7, there are no objects experiencing the same red-shift scattering effect with which we can calibrate the image. Thus, for the images of Betelgeuse, Sirius, and Aldebaran, we used the calibration from the Sun to approximate temperature. Due to the existence of some amount of interstellar gas between the star and our solar system, these values will likely be neither as consistent nor as accurate to the known temperatures of the stars.

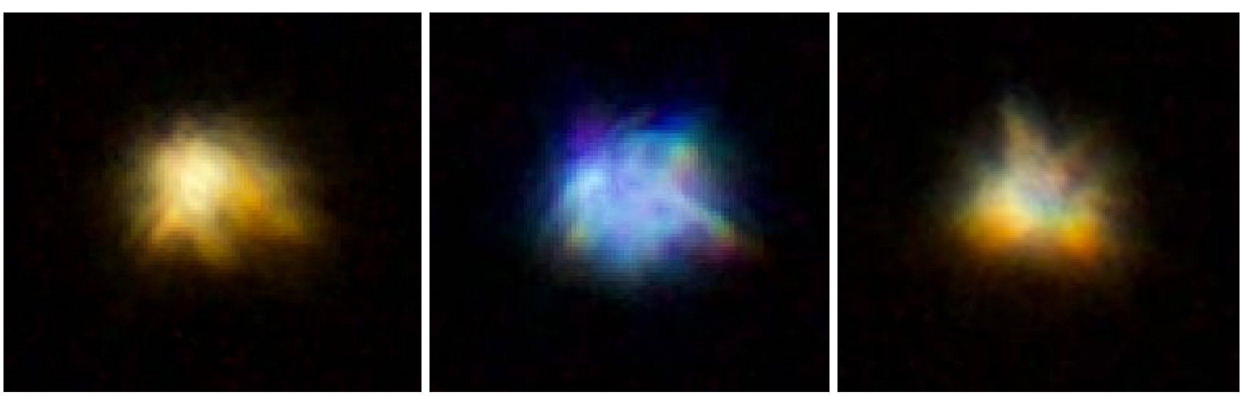

Figure 7. Non-binary stars Betelgeuse (left), Sirius (middle), and Aldebaran (right).

Using the Sun calibration, the temperatures of Betelgeuse were found to be 3368 K for the green/red ratio, 3029 K for the blue/green ratio, and 3177 K for the blue/red ratio. The known value of Betelgeuse is 3500 K, so the Sun calibration was pretty successful in approximating consistent and accurate temperatures for Betelgeuse. The temperatures of Sirius were found to be 8646 K for the green/red ratio, 9474 K for the blue/green ratio, and 9078 K for the blue/red ratio, with a known value of 9940 K. We noticed that our temperature approximations for sun-calibrated Sirius and Mizar A-calibrated Mizar B (both blue stars) the blue/green ratio, unlike for the other objects, actually gave a higher temperature than the green/red ratio (see A-1). We thought this could be due to the blue appearance of the stars, but we are not sure because the interstellar clouds still filter blue light more than red. Nevertheless, the temperatures for Sirius were largely consistent and pretty accurate with the known value, so the Sun approximation was decently successful. The temperatures of Aldebaran, using the Sun calibration, were found to be 4032 K for the green/red ratio, 3737 K for the blue/green ratio, and 3867 K for the blue/red ratio, with a known value of 3910 K. For all three stars, the results probably could have been improved if we had an object of known temperature to calibrate it with like for the binary stars. All three stars however had decently successful approximations in terms of consistency and accuracy, more so than the two binary star systems, so it is possible there are less interstellar clouds or gases between our solar system and these stars to alter the radiation spectra.

Conclusion:

The goal of this lab was to observe objects in the lab (the metal piece), in our solar system (the Sun), and in our galaxy (the stars) that were radiating spectra in the visible spectrum and analyze images taken of each to approximate their temperatures. For the metal piece, we successfully calibrated to account for imperfect calibration of the camera filter sensors. For the sun, using the perfectly calibrated transmission functions from the metal calibration, we were able to come fairly close to the known value with the green/red intensity ratio temperature approximation (the reason explained above). We also were successful in calibrating the sun image to account for atmospheric scattering. For the binary stars, we used the sun calibration to estimate temperatures of both stars in the system, then calibrate the system using the known temperature of the brighter star. For both Albireo and Mizar, we were successful in getting closer to the known temperature of the second dimmer star after this calibration. Finally, for the non-binary stars, we could not re-calibrate as there were no objects experiencing the same scattering effect as with the binary stars, but we were fairly successful in approximating the temperatures using the sun calibration.

Appendix:

A-1: Star Information Table (Picture File Name, Approximated Temperature for Ratios, Region of Interest, and Known Temperature)

Star Name	Calibration	Picture	Green/Red Ratio	Blue/Green Ratio	Blue/Red Ratio	Pixel Range (col,row)	Known Temp.
Betelgeuse	Sun	001326.dng	3368K	3029K	3177K	1391:1396,1676:1681	3500K
Sirius	Sun	001316.dng	8646K	9474K	9078K	721:723,1455:1459	9940K
Aldebaran	Sun	001350.dng	4032K	3737K	3867K	230:234,1250:1254	3910K
Albireo A	Sun	albireo.dng	3881K	2728K	3168K	800:802,1349:1351	4270K
Albireo B	Sun	albireo.dng	8817K	4254K	5541K	835:836,1303:1305	13200K
Albireo B	Albireo A	albireo.dng	11420K	9423K	10223K	835:836,1303:1305	13200K
Mizar A	Sun	001336.dng	9293K	5654K	6848K	757:760,1372:1374	9000K
Mizar B	Sun	001336.dng	8027K	5554K	6446K	770:772,1394:1396	9000K
Mizar B	Mizar A	001336.dng	7814K	8736K	8290K	770:772,1394:1396	9000K

A-2: Calibration Scaling Factors for Metal, Sun, and Binary Stars Albireo and Mizar

Calibration Image	Scaler for Red Transmission	Scaler for Blue Transmission	Scaler for Green Transmission
Metal	$\frac{1}{0.9110}=1.098$	1.1861	1
Sun	$\frac{1}{0.9970}=1.003$	0.7431	1
Albireo A	$\frac{1}{0.9355}=1.069$	0.6483	1
Mizar A	$\frac{1}{1.0093}=0.9908$	0.8033	1

A-3: Matlab Analysis Code: Lab7Script.m

```
%%Lab7 Script
%Import photo
[FileName,PathName] = uigetfile('*.dng','Select the picture file');
P=importdata([PathName FileName]);
%Display this image
figure(1);
image(P);

%% Use raw data script
[RED, GREEN, BLUE, IMAGE] = GetRAWDATAandIMAGE([PathName FileName]);

%% Plot new image to determine rectangle
figure(2);
image(IMAGE);

%% Calculate intensities in red, blue, and green
rectRed = RED(721:723,1455:1459); % 805:1257,968:1454 for sun; 886:945,1374:1439 for metal
rectRed = rectRed(:); %for sirius star 721:723,1455:1459, betelgeuse 1391:1396,1676:1681, alde 230:234,1250:1254
Ired = mean(rectRed); % for albeiro 800:802,1349:1351 other 835:836,1303:1305
rectGreen = GREEN(721:723,1455:1459); %mizar 757:760,1372:1374 other 770:772,1394:1396
rectGreen = rectGreen(:);
Igreen = mean(rectGreen);
rectBlue = BLUE(721:723,1455:1459);
rectBlue = rectBlue(:);
Iblue = mean(rectBlue);
ratGR = Igreen/Ired;
ratBG = Iblue/Igreen;
ratBR = Iblue/Ired;

%% calc density
T = [1000:10:40000]; % 2000 to 10000 changed for sun, use 1000 to 2000 for metal
dRed = SpecDens(Tr_red(:,1),T);
dBlue = SpecDens(Tr_blue(:,1),T);
dGreen = SpecDens(Tr_green(:,1),T);
IredT = sum((1./save11).*(1./save1).*Tr_red(:,2).*dRed);
IblueT = sum(save22.*save2.*Tr_blue(:,2).*dBlue);
IgreenT = sum(Tr_green(:,2).*dGreen);
% metal: save1=0.9110,save2=1.1861 sun:save11=0.9970,save22=0.7431

%% expected ratios
expGR = IgreenT./IredT;
expBG = IblueT./IgreenT;
expBR = IblueT./IredT;
figure(3);
plot(expGR,T);
figure(4);
plot(expBG,T);
figure(5);
```

```
plot(expBR,T);
TempGR = interp1(expGR,T,ratGR);
TempBG = interp1(expBG,T,ratBG);
TempBR = interp1(expBR,T,ratBR);

%% Calibration
Calib = interp1(T,expGR,9000); %5778 for sun, 1373 for metal
Scale = ratGR/Calib;
Calib2 = interp1(T,expBG,9000);
Scale2 = ratBG/Calib2;
%save1 = Scale; % save1 and save2 were scalars from metal
%save2 = Scale2; %save11 and save22 were scalars for sun
N_Tr_blue = Scale2.*save22.*save2.*Tr_blue(:,2);
N_Tr_green = Tr_green(:,2);
N_Tr_red = (1./Scale).*(1./save1).*(1./save11).*Tr_red(:,2);
N_IredT = sum(N_Tr_red.*dRed);
N_IblueT = sum(N_Tr_blue.*dBlue);
N_IgreenT = sum(N_Tr_green.*dGreen);
N_expGR = N_IgreenT./N_IredT;
N_expBG = N_IblueT./N_IgreenT;
N_expBR = N_IblueT./N_IredT;
figure(6);
plot(N_expGR,T);
figure(7);
plot(N_expBG,T);
figure(8);
plot(N_expBR,T);
N_TempGR = interp1(N_expGR,T,ratGR);
N_TempBG = interp1(N_expBG,T,ratBG);
N_TempBR = interp1(N_expBR,T,ratBR);
```

A-4: Matlab Spectral Density Function: SpecDens.m

```
function density = SpecDens(wth,Temp)
h = 6.62607004*(10^-34);
c = 2.99792458*(10^8);
kB = 1.3807*(10^-23);
density = (1./((wth).^5)).*(1./(exp((h*c)./(wth.*Temp.*kB))-1));
end
```