Lab 06: The Sun Lab

1 Light

Light acts like both a wave and a particle, as you may have heard.

Waves are traveling vibrations in space and time.

- Freeze a wave in time: you can measure a wavelength (λ, Greek letter lambda) from peak to peak or trough to trough
- Stand next to a wave: you can time how long it takes for consecutive peaks or troughs to pass by, thus you can measure a period (T) or frequency ($f = 1/T$).

The frequency, wavelength, and speed c of a wave are related as:

$$c = f\lambda$$

A **photon**, which is a particle (or quantum) of light, has energy

$$E = hf$$

where h is Planck's constant and f is frequency.

Light has a **spectrum**, which is its intensity as a function of wavelength, $I(\lambda)$. To figure out how bright an object appears to the human eye, you would add up all the light between 400 and 700 nm as

$$\int_{400\text{ nm}}^{700\text{ nm}} I(\lambda)\mathrm{d}\lambda.$$

You may see different definitions for "spectrum"; e.g., {intensity, flux, specific flux, specific intensity, brightness, irradiance} as a function of {wavelength, frequency, energy}. All mean roughly the same thing for this class.

Lastly, matter can **emit**, **reflect**, **absorb**, and **transmit** light.

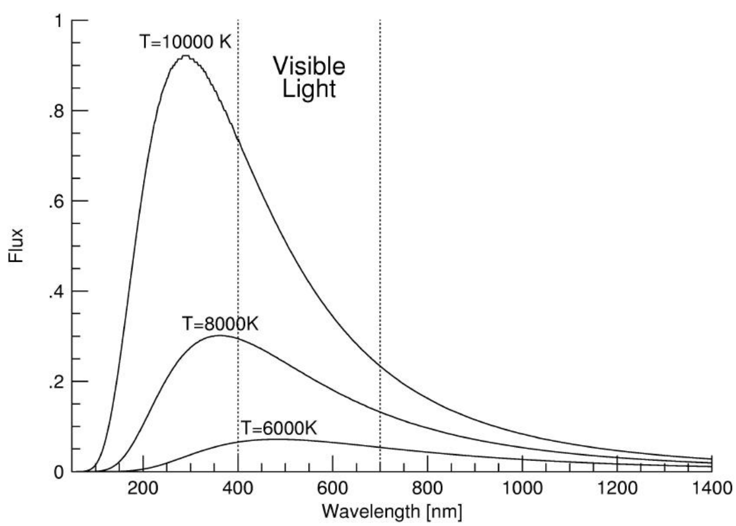
1. The speed of light, c, is constant. What does that imply about the relationship between f and λ?

2. Which form of light has higher frequency: X-rays or infrared?

3. Which form of light has more energy: microwave or visible?

4. If you shine white light (all visible wavelengths) upon a Red Delicious apple, it absorbs blue and green light but reflects red. Thus we perceive the apple as red.
   (a) What wavelengths of visible light does a snowball reflect? Absorb?
   (b) Why do black objects heat more in sunlight than white objects?
   (c) What happens if you shine a blue light on a red apple? What about a red light?

All objects emit light. That light has a **blackbody** spectrum, dependent only on the emitting object's temperature.



Credit: R. Pogge, T. Thompson (OSU)

Hotter things emit more brightly and emit more at small wavelengths (so, they look bluer to the eye). The wavelength where a blackbody emits most strongly is given by:

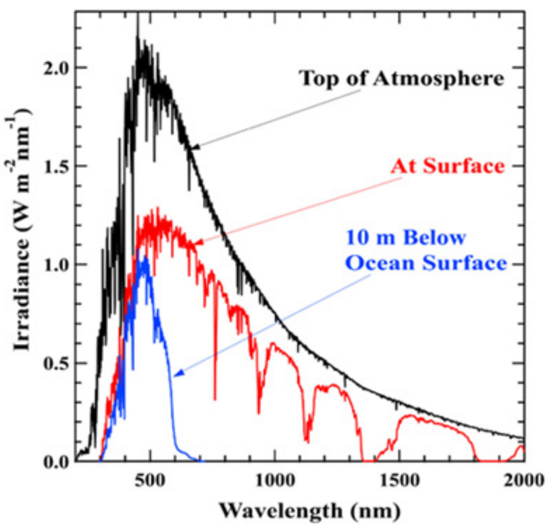
$$\lambda_{\mathrm{max}} = \frac{0.29 \text{ cm K}}{T}$$

where T has units of Kelvin.

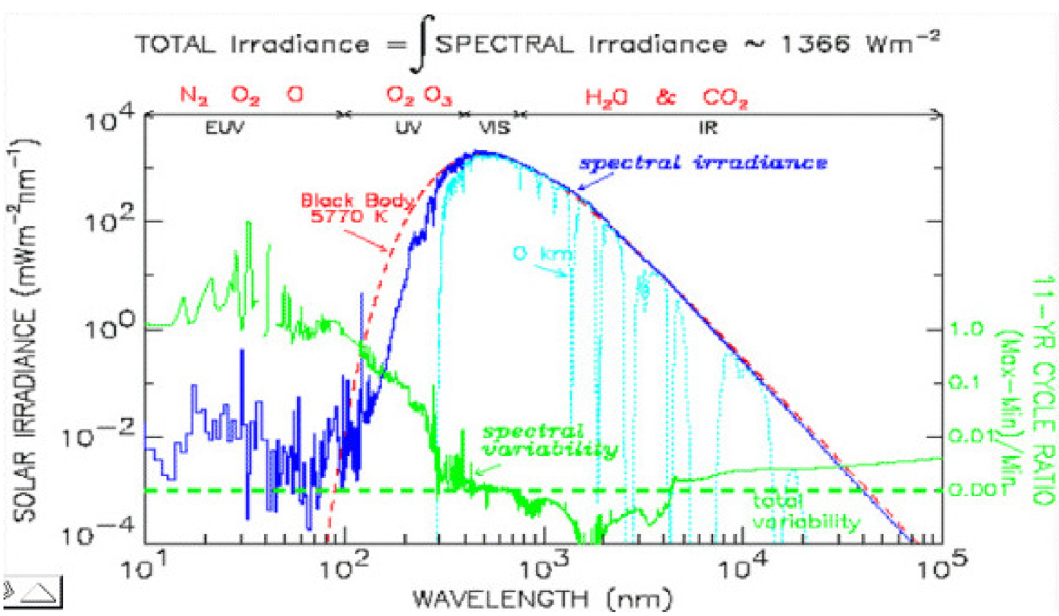
1. What would a hot star ($T = 10,000$ K) look like to your eye? What is its λ_{max}?
2. What would a cool star ($T = 3500$ K) look like to your eye? What is its λ_{max}?

3. The hot star emits more red light than the cool star. But, the hot star looks blue and the cool star looks red. Why is this? Explain in your own words. You can check by looking at two very bright winter-sky stars, Sirius (hot) and Betelgeuse (cool), with your naked eye – which hopefully we'll do later this term!

Finally, here are a few plots of the Sun's spectrum.



Solar spectrum above Earth's atmosphere, i.e., space (black), at Earth's surface (red), and underwater (blue). Credit: F. Bagenal (CU Boulder)



Solar spectrum from space (dark blue), at Earth's surface (cyan), and model blackbody spectrum for Sun's surface temperature (dashed red). Spectral variability (light green, right y-axis) shows how much the Sun 's spectrum varies over a solar cycle. The Sun 's UV and EUV intensity can change by up to $2\times$, whereas the sun's visible intensity only varies by 0.1%. Credit: NRL/NASA, posted by D. Jeffery (UNLV)

The dips in the spectrum are **absorption lines**. Atoms in both the Sun's atmosphere and Earth's atmosphere absorb light at very specific frequencies, causing us to miss some blackbody spectrum light that would have otherwise reached us.

2 The Sun

We'll watch a series of videos (`http://www.pbs.org/wgbh/nova/labs/videos/#sun`) introducing solar science and the Helioviewer.

For Sections 2 your answers can be brief; a few words or a sentence will do.

1. What causes the Sun's magnetic field to become both stronger and more tangled?

2. How long does it take the Sun to rotate once on its own axis?

3. Name two events that can be caused by magnetic reconnection.

4. Define "solar maximum".

5. Why do sunspots look darker than the rest of the Sun ?

6. What are two ways that Earth is protected from solar storms?

7. What causes auroras?

8. Why are humans more vulnerable to big solar storms now than in 1859?

9. Is the following statement true or false? "The longer its wavelength, the more energy light carries." Explain why.

10. Why is it useful for solar research to have instruments that can look at wavelengths besides the visible that we can see with our eyes?

11. If you want to look at a hotter part of the solar atmosphere, do you want to look at smaller or larger wavelength light?

12. What is special about the STEREO mission?

13. Describe the instruments on the SDO (AIA, HMI).

3 Forming Questions

Hop onto Helioviewer: http://helioviewer.org/ Your TA will walk through the features. Play around for a bit. Several resources – including a guide to SDO/AIA images – are linked towards the end of this lab.

Now, you will generate some research questions about the Sun. What does that mean? That often (but not always) means investigating cause-and-effect, e.g. by looking for correlation.

For example, one may ask: what features in the Sun develop before a flare? Suppose you do find something at 171 Åjust before one flare. That can lead to a host of follow-up questions: is more stuff happening at other wavelengths, before this flare? Can you relate the feature to the flare properties and aftermath? Are the same features seen for other flares? If not, why?

Ask many questions, and strive to form *testable* questions and *falsifiable* hypotheses. Explore the data as you go – you will probably answer some of your simpler questions just by looking at the data, and gain ideas for new questions. I recommend recording all questions/ideas you've considered, even those that you discard; you might later realize that a seemingly-intractable question is quite doable!

1. Record at least 3 research questions, and explain how you would investigate these questions using the available data. Please come up with questions **individually** even if you are working in a group; everyone's questions in your group should be different, but feel free to discuss ideas with other students.

4 Investigation

Find a partner and choose a research question to investigate in depth. **Run your question by the TA before you begin.** As you study the data, your question may change slightly, or you may even wish to throw it out entirely. That's OK and encouraged! But, please explain in your write-up how/why you changed course.

Write-up expectations

Your lab write-up should make very clear:

1. What is the question you are investigating?

2. What is your plan to answer this question?

3. How did you execute the plan, how did it go?

4. Explain the conclusion you came to, and how the data support this conclusion.

You will be graded on demonstrated effort, scientific thinking, and clarity of presentation. Your conclusions should be supported by the Helioviewer data, but you will not be penalized for slightly incorrect conclusions due to insufficient time/data. Pretend you are a scientist writing a rough draft of a scientific paper (which you are!). Write down your thinking as you go along. Do use complete sentences or coherent sentence fragments.

Don't assume that your TA can see what you see. Think about what you will highlight, and be quantitative when necessary. Regarding an appropriate level of detail, here are two example statements that describe the same feature:

- "...filament A (x=963", y=165" at 2020/02/02 02:02:02UT) is twice the diameter of its underlying sunspot group (IX) and persists for the sunspot group's entire journey from left to right limb of the Sun; filament A seems to vibrate with respect to group IX when we toggle images with 1 hr spacing, but we saw no vibration when toggling with 10 minute or 1 minute spacing, though this could have been due to image noise or limited human eye sensitivity..."
- "...we saw a big, dark bar over one sunspot group, and decided to look for more examples; we found 20 similar bars in Feb 01–28, 2020..."

Each statement communicates very different information. Neither one nor other is "better"; "better" depends on context. But, if you are unsure, err on the side of more detail.

5 Conclusions

1. What did you like or dislike about this lab?

2. Any feedback/suggestions?

3. Any remaining questions?

A About the Sun

- Solar cycle: 11 years
- Sunspot counts, 2008-2019:
  https://www.swpc.noaa.gov/products/solar-cycle-progression
- Sun's rotation period: 24.5 days (equator), 38 days (poles)
  Sun's rotation period, synodic (equator): 26.24 days
  Sun's rotation period, synodic (lat=26 deg): 27.2753 days, called the Carrington period

B Data catalogs and archives

A few examples, sorted in rough descending order of (anticipated) usefulness. Google around to find more!

- SOHO/LASCO coronal mass ejections https://cdaw.gsfc.nasa.gov/CME_list/ manually identified by humans
  - Example: movie of strong CME, 2011/05/09 20:57:26UT
  - Example: movie of strong CME, 2012/07/23 02:36:05UT
  - Note that one CME is accompanied by a burst of X-rays, but the other is not. Why??
- Hinode/XRT-detected X-ray flares (2006-2017) http://xrt.cfa.harvard.edu/flare_catalog/all.html
- RHESSI-detected X-ray flares (2002-2018) http://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt with start and end times, peak X-ray photons per second ("P c/s", peak counts/second), total counts, flare's position on the Sun . Warning, text file size is 17MB.
- ACE solar wind measurements (1998-2018) http://www.srl.caltech.edu/ACE/ASC/DATA/level3/summaries.html including wind velocity, particle density, magnetic field, etc. sensed at a location between Earth and Sun (quite close to Earth, at L1 Lagrange point). You can ask, for example, what features on the Sun correlated with high levels of carbon ions hurling towards Earth?

C Helioviewer help!

- The "measurement" values are the wavelength, in Angstroms (Å), of the filter used to obtain the image. 1 Å $= 10^{-10}$ m = 10 nm.
- If the date/time turns red or yellow, that means there is not data of the requested type taken close to the date/time you asked for. Even if the date/time is green, it's best to check to see what time is actually being displayed, as opposed what time you input.

- Helioviewer User guide:
  http://wiki.helioviewer.org/wiki/Helioviewer.org_User_Guide_3.1.0
- Helioviewer "Features and Events" annotations on Helioviewer:
  http://wiki.helioviewer.org/wiki/HEK_Features_and_Events
- Glossary of solar physics terms:
  https://hesperia.gsfc.nasa.gov/sftheory/glossary.htm
- What do SDO images show?
  https://www.nasa.gov/mission_pages/sunearth/news/light-wavelengths.html
- What do SDO images show? (same image, slightly more detailed explanation)
  https://www.nasa.gov/content/goddard/how-sdo-sees-the-sun

D Cheat-sheet of Helioviewer data

- SDO: 2010 to present
  - Cadence: 30 seconds (for same wavelength image)
  - AIA: 94, 131, 171, 193, 211, 304, 335, 1600, 1700, 4500 Å
  - HMI: continuum, magnetogram
- SOHO: 1995 to present
  - Cadence: 12 minute (?)
  - EIT: 171, 195, 284, 304 Å
  - LASCO: C2 (inner), C3 (outer) white-light coronagraph
  - MDI: continuum, magnetogram
- STEREO-A: 2007 to present
- STEREO-B: 2007 to 2014
  - Positions: https://stereo-ssc.nascom.nasa.gov/cgi-bin/make_where_gif
  - Cadence: 3 minute (?at best)
  - SECCHI EUVI 171, 195, 284, 304 Å
  - SECCHI COR1 white-light coronagraph (inner)
  - SECCHI COR2 white-light coronagraph (outer)
- TRACE: 1998 to 2010
  - 171 Å(ionized Fe), 195 Å(ionized Fe), 284 Å(ionized Fe), 1216 Å(neutral H), 1550 Å(ionized C), 1600 Å(continuum), 1700 Å(continuum)
- Yohkoh: 1991 to 2001
  - Soft X-ray telescope
  - Some movies at http://ylstone.physics.montana.edu/ylegacy/

- Hinode: 2006 to present
  - XRT: an X-ray telescope
  - Data are a bit challenging to use: small cut-outs and lower cadence, and need to decipher filter-wheel configuration
- PROBA-2: 2009 to present
  - Cadence: 1 minute
  - SWAP: 174 Å