Lecture 29: Forbidden and Scattering Coronal Lines

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Last class

- We moved to another physical regimes!
- RTE is somehow simplified, as we mostly just integrate the emissivity, but it is actually a problem
- We saw what are Emission Measure (gives us a rough idea about the electron number density) and Differential Emission measure (electron density at given temperature)
- This class: more physics of line formation, more examples!
- I again drew up on some resources that I am listing here (and will link at the webpage)
Something to read:

- Steve Cranmer’s and Alexandar Kosovitchev lecture slides
- Alin Parashiv’s lecture from the last year’s COLLAGE (Lecture 27 from COLLAGE 2020)

There are probably much more, so feel free to let me know and I will update!
Let’s recap what happens in the corona

- It is **hot** and **tenuous**
- High ionization, (also excitation?), high thermal broadening, low opacity...
- But also non-thermal broadening, non-Maxwellian velocities and whatnot!
How does Corona actually look like?

• I will give you my usual answer – depends on the wavelength

• Except here, instead of looking at different depths at different wavelengths, in the same spectral line (recall hw1 p3 and hw2 p2), we look at individual spectral lines that form at different temperatures, and are sensitive to density (or density squared) and figure out the temperature / density structure.

• There are also other methods and we will talk about these today
Remember this?

Los integration probes different regions with different conditions!

\[ I_\lambda = \int_0^s j_\lambda(s') ds' \]

\[ j_\lambda = n_u A_{ul} \frac{hc}{4\pi \lambda} \phi_\lambda \]
How about this?

- First assume that levels are in a **statistical equilibrium** (total amount of transitions to the level is equal to the total amount of transitions from the level).

- Let’s try to write **statistical equilibrium equation** for this two level atom.

- **Reminder:** We defined “Rates” at some point. For example collisional rates (number of the appropriate collisions per s) were denoted with $C_{ij}$, and so on.

$$
n_l(B_{lu} J + C_{lu}) = n_u(A_{ul} + B_{ul} J + C_{ul})
$$

Best collisional partners are electrons, so there is electron density hidden here in “C” coefficients.
Collisionally vs scattering dominated lines

\[ n_l (B_{lu} J + C_{lu}) = n_u A_{ul} \]

• The right hand side goes into our expression for emission
• Depending on which effect dominates, we distinguish
• **Collisionally dominated lines**, where the excitation is collisional
• **Scattering dominated lines**, where the excitation is radiative. This is scattering similar like in the case of prominences.
Example, Fe IX 171 Angstrom (AIA line)
Modeling scattering lines

- For these ones, radiative absorption is the excitation source, so we have:

\[ n_l B_{lu} J = n_u A_{ul} \]

\[ j_\lambda = n_l B_{lu} \frac{hc}{4\pi\lambda} \phi_\lambda \times J \]

- What does this look like? If you don’t remember, can you guess from dimensional analysis?
We get an equation that should not surprise us that much considering what we talked about in our scattering fairytales :-) 

\[ j_\lambda = n_l B_{lu} \frac{hc}{4\pi \lambda} \phi_\lambda \times J \]

\[ j_\lambda = \chi_\lambda \times J \]

\[ S = J \]

Source function is equal to mean intensity. Amount of emitted photons is proportional to the amount of the “absorbed” ones (not surprising since it’s pure scattering!)
Remember this problem?

- Q: “In which case will scattering emissivity be higher?”
Scattering regime - reminder

- In most general case emission and absorption coefficient follow from the solution of the **statistical equilibrium equation**

- In a two-level atom, with some approximations, **source function is a combination of thermal and scattering contribution** (remember epsilon)

- If we neglect thermal (prominences, “high” corona) contribution, we get **source function equal to the mean intensity**

- Finally, in the most, (but note works of, say Wood, 2000) parts of corona optical depth is so low we can just integrate emission coefficient along the line of sight

- Not super different from the continuum scattering case!
And corona is the place for scattering

- So called **K-corona**, created by the scattering of the photospheric light on the free electrons.

- What do you think, how does the brightness relate to the electron densities? *(2 mins)*

- Problem credits: Lectures by A. Kosovitchev (Stanford)
And corona **is** the place for scattering

- What do you think, how does the brightness relate to the electron densities?
- That’s right, linearly!

Because:

$$j_\lambda = \chi_\lambda J = n_e \sigma_{\text{Th}} J$$

$$I_\lambda = \int j_\lambda ds = \sigma_{\text{Th}} J \int n_e ds$$

“Column density”

From Stoitchkova, 2007
Let’s estimate the density of K corona!

- There is a reason the corona is often visible only during eclipse. It’s intensity is $\sim 10^{-6}$ of the disk intensity!
- I tell you that the sigma (cross-section for Thomson scattering), is $3.3 \times 10^{-25}$ cm$^2$
- Estimate (to an order of magnitude), the density of the K corona!
- Can anyone first give me their expectations? For reference, in homework 1, you got something like $\sim 10^{15}$ cm$^{-3}$ total particles for a slab of gas at 7000K at Pressure of 70 Pa (This is 700 dyne/ cm$^2$ which could be upper photosphere/lower chromosphere)
Solution!

\[ I_d = I_0 \cdot 10^{-6} \]

\[ I_d = \sqrt{\mu_0 I_0 ds} \approx \sqrt{\mu_0 I_0 \Delta S} \]

\[ j_d = ne \cdot \frac{v}{b_{TH}} J \approx ne \cdot 6_{TH} \cdot I_0 \]

\[ n_e \approx 10^7 \text{ to } 10^8 \text{ cm}^{-3} \]
You might have also heard about F-corona

- Similar thing but the scattering is on dust particles, instead of free electrons
- When this scattering is happening on particles very far away from the Sun (in interplanetary space) we call it “Zodiacal Light”
- Does anyone know any other notable works by this author?
For example “We will Rock You” (May, 1977)

Freddie Mercury and Brian May (NME, 2019)
Back to F- vs K- corona

- Corona is really really faint
- Judging from what we know this allows us to learn to infer that the number densities in solar corona are very very low.
Back to F- vs K- korona

- F is dust, K are electrons
- F is called F because you see Fraunhofer lines in the scattered light
- How can this be?

From Koutchmy et al, 2019 (of course :))
Back to F- vs K- korona

- F is dust, K are electrons
- F is called F because you see Fraunhofer lines in the scattered light
- **Because dust particles are just “redirecting” the incident light.**
- If there is incident absorption spectrum, there is an outgoing emergent spectrum.

\[ j_\lambda = n_e \sigma_{dust} J_\lambda \]
Why does not K corona show the absorption lines then?

- The answer allowed Grotrian (1931) to estimate the temperature of corona to millions of K.
- How? What does temperature do?
- Think about what particles are doing the scattering, and about their mass.
- Dust is heavy, electrons are light...
- **Think for 3 mins about this and let’s see what we come up with.**
Electrons move fast

- Since electrons move fast, they are somehow “redistributing the light”
- Even though scattering is “coherent”, it is so in the frame of the electron!
- For us the emission is extremely smeared because the electrons have huge velocity dispersion
- The incident spectrum is basically convolved with a very wide kernel and we obtain a “flat” spectrum
- Grotrian (1931) estimated that velocity dispersion for this has to be huge and so do the coronal temperatures
Or via (bad) sketch
Now, E-corona (emission lines), and prominences, and loops

- Let’s try and come up with an explanation for the following:

  How come these objects exhibit emission lines when they are illuminated by the absorption ones?

- 3 mins to think and present the ideas
The trick is in the so called “redistribution”

- Emission depends on the population of the upper level and scales with wavelength as the emission profile (used psi on purpose!)

\[ j_\lambda = n_u A_{ul} \frac{hc}{4\pi \lambda} \psi_\lambda \]

- The upper level is populated by *all the incoming radiation* weighted by the absorption profile:

\[ n_u A_{ul} = n_l B_{lu} J = n_l B_{lu} \int \int I(\theta, \phi, \lambda) \frac{\sin \theta d\theta d\phi}{4\pi} \phi_\lambda d\lambda \]

Incoming radiation!
In the most general case

- Line redistribution is extremely complicated and happens both in wavelength **as well as direction** (emission is **not** isotropic)

\[
I(\Omega, \lambda) = \int \int R(\Omega', \Omega, \lambda', \lambda) I(\Omega', \lambda') \frac{d\Omega'}{4\pi} d\lambda
\]

- Once we move to the polarization this becomes even more complicated :-)

Scattered radiation

Incoming radiation

Redistribution function
One of the super complicated ones – Ly alpha
“Simple” coronal redistribution

- The Lyman alpha line is formed in the solar atmosphere (Transition region line), but we can see it as a coronal scattering line off limb.

- How does that work? We end up with neutral hydrogen in ground level and these absorb all the illuminating radiation and redistribute it:
  - White – illuminating
  - Red – scattered radiation

- Scattered radiation “picks up” local profile

![Graph showing radiation distribution](image-url)
Now a question for you

What happens to J if my blob is illuminated by a narrow emission line (and weak continuum), and the blob has a large upward velocity? (3 mins)
Doppler dimming

- Due to Doppler shift, the blob has less radiation to scatter, so the mean intensity decreases.

- We look from the side, and we see less light! :O
Doppler dimming

- Due to Doppler shift the blob has less radiation to scatter, so the mean intensity decreases

- We look from the side, and we see less light! :O

- Right, we see line dimming due to outflow velocities for various broadening temperatures

\[ T_H = 0.3, 1, 3 \text{ MK} \]
Hints of H I Lyα Doppler dimming were first seen in data from 1980 rocket flight of a UV coronagraph spectrometer (Kohl, Withbroe, et al.)
There can also be doppler brightening (not boosting!)
Finally a note on forbidden lines!

Voulgaris et al.
Forbidden lines and what’s the trick

- At first people could not figure out to which elements these lines belong
- Turns out these are the lines with extremely low Einstein coefficient of emission
- Extremely low means $10^1$ to $10^3 \text{ S}^{-1}$
- What then? Well, collisional de-excitation competes with radiative one

$$n_l(B_{lu} J + C_{lu}) = n_u(A_{ul} + B_{ul} J + C_{ul})$$
Following Del Zanna & Mason (2018)

- The upper level is the one which is “metastable” (radiative transition downward is unlikely but will eventually happen)

\[ n_l (B_{lu} J + C_{lu}) = n_u (A_{ul} + B_{ul} J + C_{ul}) \]

\[ n_u = \frac{n_l n_e \Omega_{lu}}{n_e \Omega_{ul} + A_{ul}} \]

- If A wins \(\rightarrow\) quadratic dependence on the electron density

- If collision win \(\rightarrow\) linear dependence on electron density (but if too much density no line, why?)
If it’s intermediate?

- In the intermediate case, it is something in between and we can compare couples of forbidden lines to infer electron density.

From Del Zanna & Mason 2018, following Mason 1999. SOHO observed these lines.
And some non-coronal coronal lines!

Apparantly, the magnetic fields in the coronal loops are much (x10) stronger than we expected!

Kurdze et al. (2019)
That’s all folks!

- We examined some spectrum formation mechanisms in the corona when the scattering dominates.
- Once again it turned out the lines are special because they have steep dependence of absorption/emission of wavelength.
- We also mentioned forbidden lines, they are good density diagnostics (also in interstellar medium, e.g. planetary nebulae, SNRs).
- Next class: Playing with some example inversion data and wrapup!
- Questions? Suggestions? Comments?