Chromospheric Spectral Line Diagnostics of Solar Flares (2)

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Overview

Lecture plan

1. Today: observational overview
   a. overview of some impt. solar flare chromospheric spectral line observations
   b. Begin flare radiation hydro

2. Tues: Equations of (flare) radiation hydrodynamics

3. Activity

Does everyone have python 3.x via jupyter notebooks?
Announcements

Living Reviews in Solar Physics (LRSP) article: Toriumi and Wang 2019 “Flare Productive Active Regions” is a great starting place if you’re interested in learning more about sunspot rotation, PIL formation, etc...

https://www.springer.com/journal/41116
(lots of great review articles on other topics as well!)
IRIS data of an X-class solar flare
credit: Adrian Daw (GSFC)
Hydrogen broadens more than everything else

Neidig 1984

Neidig & Wiborg 1984
Collisions of Hydrogen with Charged Particles

A topic that needs its own course! Analogous to the Zeeman effect (magnetic fields) but for electric fields (the “Stark-Lo Surdo effect”).

Splitting of degenerate orbital angular momentum states $\ell$ due to an external electric field (i.e., a collision)

$$\Delta E = \frac{3e\alpha}{2} nq \times E\text{-Field}$$

$$\Delta E \propto n^2 \text{ for large } n.$$  

Ca II, Mg II, He I, also have perturbed levels but not nearly as much.

See Tremblay & Bergeron 2009
Explanation of ‘saddle point ionization’ (and more)

Springer Handbook of Atomic, Molecular, and Optical Physics (2006)
“Rydberg Atoms” textbook by Gallagher (right):

studies of the Balmer series in electric fields of up to $10^6$ V/cm. The Balmer lines exhibit a splitting which is approximately linear in the electric field, and the components actually disappear at well defined values of the electric field due to field ionization of the Rydberg state.

While the Bohr atom is of no help in understanding the splittings of the Balmer lines, using it we can calculate the field at which a state is ionized by an electric field. Consider a H atom with its nucleus at the origin in the presence of an electric field in the z direction. The potential experienced by an electron moving along the z axis is given by

$$V = \frac{k}{r} + Ez$$

(1.11)

and is shown in Fig. 1.3. Only electrons with energies lower than the local maximum of the potential, at $z = -1000a_0$, are classically bound. In the real three dimensional potential the local maximum at $z = -1000a_0$ is a saddle point, and electrons with energies above the saddle point of the potential are ionized by the field. The potential at the saddle point is given by

$$V_s = -2\sqrt{kE}.$$  

(1.12)

If this energy is equated to the energy of the Rydberg state, $-Ry/n^2$, we find the classical field for ionization of a state of principal quantum number $n$

$$E_i = \frac{Ry^2}{4n^4}.$$  

(1.13)

This formula is usually encountered in atomic units, in which it reads

$$E_i = 1/16e^4.$$  

(1.14)

In the next chapter we shall introduce atomic units. Although we have derived Eq. (1.13) with no regard for tunneling or the shifts of the energy levels in an electric
Chromospheric solar flare Hyd. lines are broad and bright, often with striking Doppler red or blue shifted features.

Hα (656.3 nm)
Ichimoto & Kurokawa 1984

Original spectra

red satellite component: RWA = red wing asymmetry

Difference (“Excess”) spectra
Two Line Components in Solar Flares

**Mg II, Si II, C I, Fe I, and Fe II**

Bright emission line around rest wavelength (1), clear and near-ubiquitous evolution of (2) over time.

Synthetic Fe II spectra from snapshots of rad-hydrodynamic simulations show salient features of this evolution!

- Proposed origin: Two line components (+ continuum) originate from chromospheric condensation (2) and heated layers below (1) below (see Kowalski et al. 2015, 2017, Cauzzi et al. 2020)

Would not know that this was NOT a single broadened line if didn’t have time-resolution!
Graham, Cauzzi et al. 2020 *ApJ*

Fe II in a different flare:

Fe II 2814.45 Small $\tau$

Fe II 2832.39 Larger $\tau$

Kowalski et al. 2017
**Observed (Symmetric) Mg II broadening much greater than theory and/or models**

Updated collisional broadening theory (STARK-B) is 30x too small.

Broadening of non-Hyd lines not just (“micro”)turbulence b/c line wings are Lorentzian.

Are we missing heating in the deep chromospheric flare layers where wings formed, or missing other nonthermal broadening (see Zhu+19)?

Profiles produced from the RH code (Uitenbroek 2001), snapshots from RADYN code (Carlsson & Stein 1997, Allred et al. 2015)

Zhu et al. 2019
Variations of the microturbulence parameter not as promising
Quite a variety of Hα profiles observed!

Canfield et al. 1990
Many such MCCD spectra available for a student project!

Johns-Krull et al. 1997
Even more behaviors revealed in recent years!

Fabry-Perot imaging spectroscopy with IBIS/DST and CRISP/SST (narrow wavelength window (+/- 1.5Å), low time-res, but large FOV)

Kuridze et al. 2015
(CRISP)
Even more behaviors revealed in recent years!

Fabry-Perot imaging spectroscopy with IBIS/DST and CRISP/SST (narrow wavelength window (+/- 1.5Å), low time-res, but large FOV)

Kuridze et al. 2015 (CRISP)

In the activity you’ll see how this can be generated first by an upflow then a downflow (counter intuitive).
Even more behaviors revealed in recent years!

Fabry-Perot imaging spectroscopy with IBIS/DST and CRISP/SST (narrow wavelength window (+/- 1.5Å), low time-res, but large FOV)

(IBIS)

Druett et al. 2017 (CRISP)
Solar Flare Emission Line Profiles:

- Symmetric profiles.
  - Hyd. lines are much broader than other lines (well-observed in solar flares)
    - often (but not always!) observed in stellar flares: Hawley & Pettersen 1991
    ■ Look for Yuta Notsu et al. 2021!
  - Unexplained symmetric broadening of each component
  - Unresolved, symmetric turbulence? (Doyle et al. 1988)

- Asymmetric profiles with two clear broad line components of Fe II, Mg II, Si II, Fe I, Hα.
  - Now a well-established temporal evolution of redshifted satellite component
  - Unexplained symmetric broadening of each component
    - Current models/theory of collisional broadening fall far short

- Asymmetric variations near line core, and striking blueshifts (Eason et al. 1992)!

- How do we (begin to) understand all these types of profiles?
Observationally:

1) Spatial resolution!
2) Need to know the time evolution!
   ● see Graham, Cauuzzi, et al. 2020

Thank you, Sol, for your warmth!
Ingredients of flare radiation hydrodynamics (RHD)

Time-evolution of (nearly) everything, resolve the first second
Response of photosphere, chromosphere, transition region, and corona (a self-consistent atmospheric model)
An adaptive grid to resolve gradients
The physics of how particle beams deposit energy in this atmosphere
We need actual model spectra to compare to observations!

Time-dependent atomic physics and radiative transfer
Also would like to simulate other types of stars (different gravity)

If require all of these, we have to work with only one spatial dimension.
The RADYN code (RAdiation hydroDYNamics)

Abbett (1998), Abbett & Hawley 1999
Allred et al. 2005, 2006
Allred, Kowalski, and Carlsson 2015
FP module: Allred et al. 2020
Many papers not listed studying flares

Source code and output: you will work with the output.

Ongoing development: first public release via Github (v1.1), more to come!