

# Spectral Line Imaging

Narrowband imaging

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# Spectral line imaging

## Useful references:

- ▶ The ASTR 203 notes
- ▶ D.E. Osterbrock & G.J. Ferland, 2006, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, chapters 1–4
- ▶ The ASTR 244/444 HII region long form lesson
- ▶ D.S. Goldman, 2013, *Narrowband Imaging in Lessons from the Masters*, ed. R. Gendler (NY, Springer), pg. 115–130.

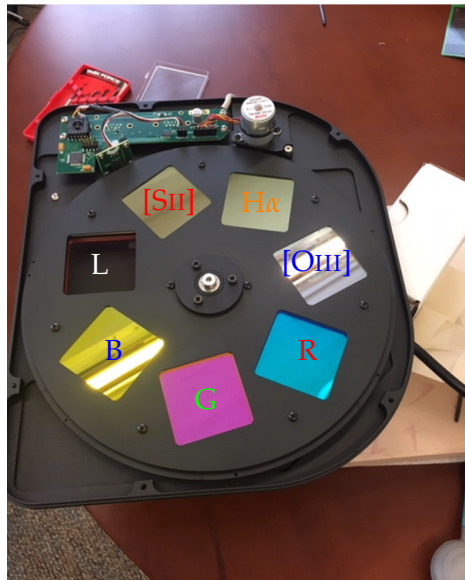


M27, LRH $\alpha$ GB, from Mees

# Spectral line imaging at visible and infrared wavelengths

All spectroscopy involves the use of interference to distinguish one wavelength from another.

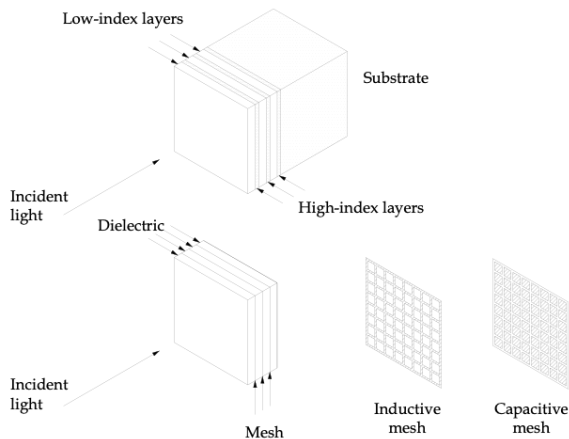
- ▶ The larger the phase difference between signals — or path-length difference, in most of our applications — the more finely the wavelengths can be discriminated.
- ▶ **Spectral resolution**,  $\Delta\lambda/\lambda$  at wavelength  $\lambda$ , is characterized by the instrument's bandwidth  $\Delta\lambda$  for a truly monochromatic signal.
  - ▶ Two signals at wavelengths separated by  $\geq \Delta\lambda$  are **resolved**; otherwise, they are **unresolved**.



## Interference filters

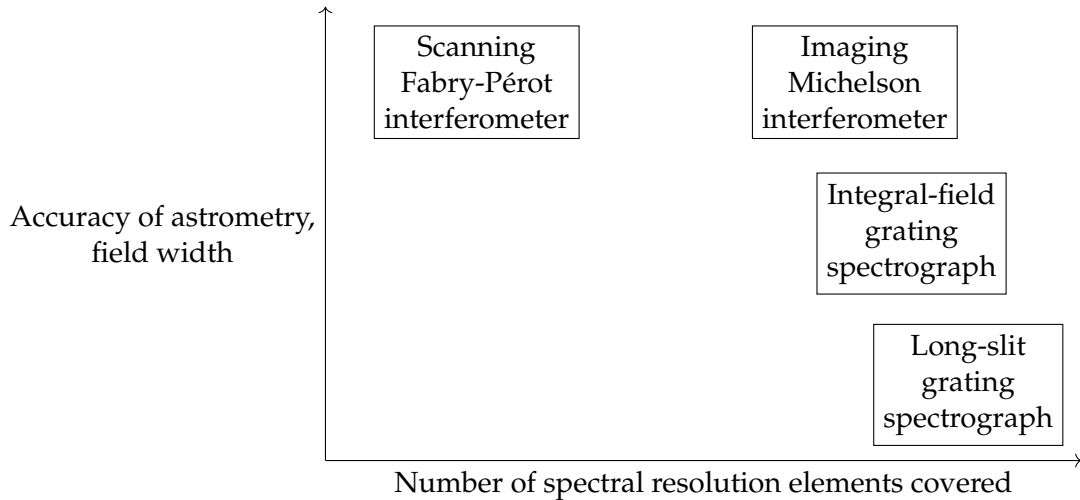
At Mees, we use multilayer dielectric interference filters in front of the CCD to make spectral line images.

- ▶ See the [ASTR 203](#) notes to learn how these are designed and built.
- ▶ Advantages: compact, extremely uniform in transmission and bandwidth.
- ▶ Disadvantages: Non-adjustable, hard to get high-enough spectral resolution to isolate individual lines, not the most sensitive.
- ▶ In some wavelength ranges, extra filters are needed for off-line wavelengths to subtract the continuum emission.



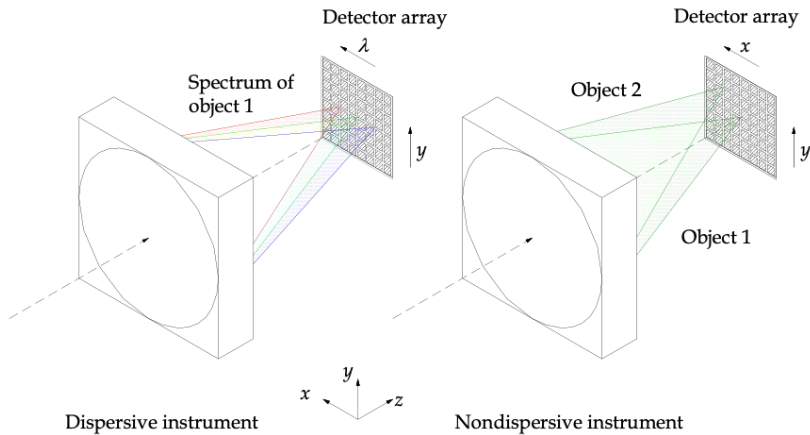
# Spectrographs

More sophisticated and more wavelength-selective instruments



# Spectrographs

Use of detector arrays with such instruments:



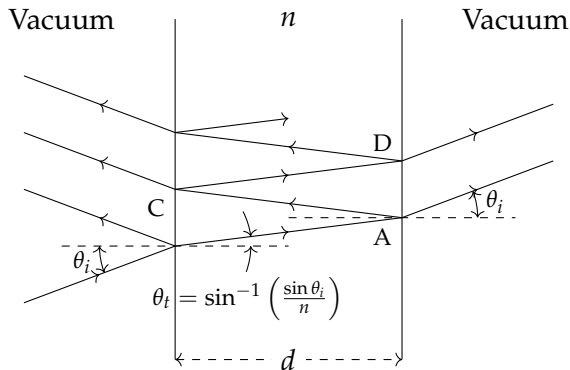
E.g. Long-slit grating spectrograph or integral-field spectrograph.

E.g. Fabry-Pérot interferometer or Michelson interferometer

# Scanning Fabry-Pérot interferometer

Best for high-resolution imaging of single lines or line profiles.

- ▶ High-reflectivity ( $r$ ), low-absorption, parallel mirrors whose (wide) optical separation  $nd$  can be controlled and precisely scanned.
  - ▶ Adjust  $d$ : piezoelectric scanning
  - ▶ Adjust  $n$ : pressure scanning

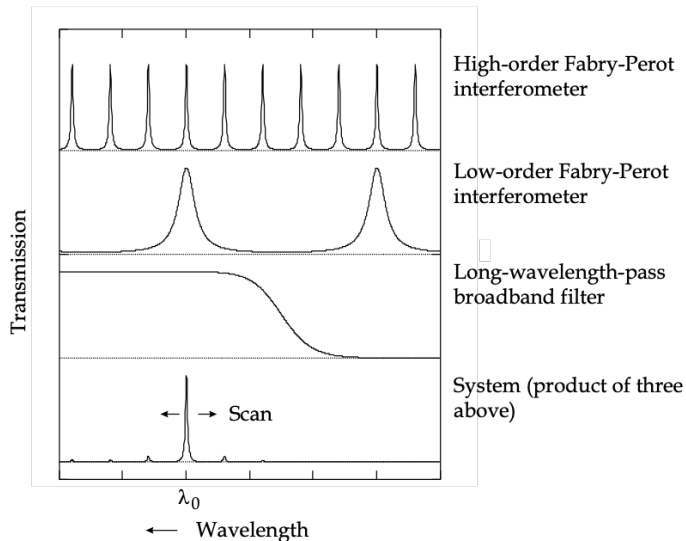


Each pixel sees  $\lambda$  at a resolution  $\Delta\lambda/\lambda$ , where

$$\frac{2\pi dn \cos \theta_t}{\lambda} = \pi m \quad \frac{\Delta\lambda}{\lambda} = \frac{1}{mQ} \quad Q = \frac{\pi r}{1 - r^2} \quad r = \frac{n - 1}{n + 1} \quad (m = 0, 1, 2, \dots)$$

# Scanning Fabry-Pérot interferometer

Usually, a sequence of 2–3 FPIs must be used to isolate a single large- $m$  order of the scanning one.

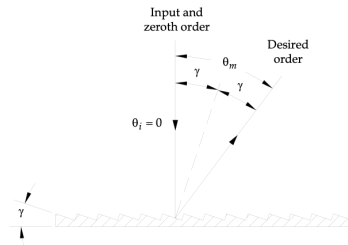




# Long-slit grating spectrograph

Best for point sources, or objects in which only one spatial dimension is important.

- ▶ Detector array sees a long wavelength span at each pixel along a 1D strip of the sky.
- ▶ Spectrograph's entrance slit, usually 2–10 pixels wide, is adjustable for seeing but at the cost of spectral resolution.
- ▶ Can only make spectral images by stepping the telescope in the direction perpendicular to the entrance slit, hopefully by a fraction of the slit width per step. (Does not work great.)



Each pixel sees  $\lambda$  at resolution  $\Delta\lambda/\lambda$ , where

$$a(\sin \theta_m - \sin \theta_i) = m\lambda \quad \frac{\Delta\lambda}{\lambda} \geq \frac{1}{mN} \quad m = \dots, -2, -1, 0, 1, 2, \dots$$

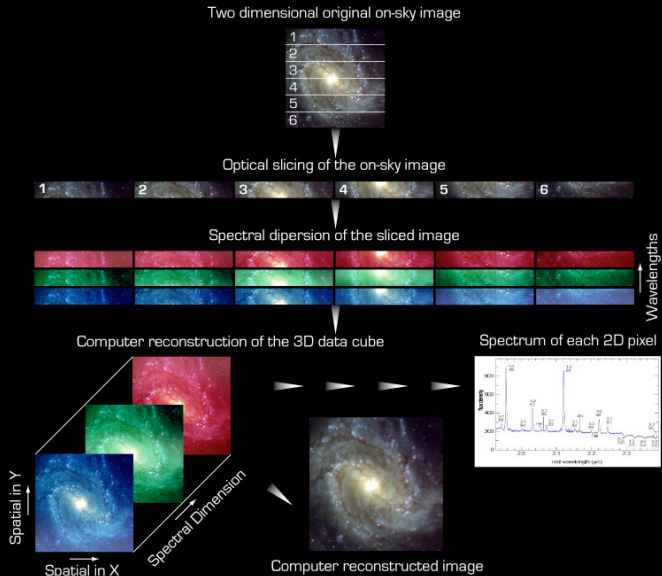
and  $N$  is the number of grating rulings illuminated.

# Integral field spectrograph

Best for full spectra of each pixel in a relatively small neighborhood around a compact object.

- ▶ Optically slice up the 2D field and image each slice along a different segment of the slit of a grating spectrograph.
- ▶ Then reconstruct the data cube after detection.
- ▶ Invented by Ira Bowen in the 1930s, before CCDs or computers.

ESO

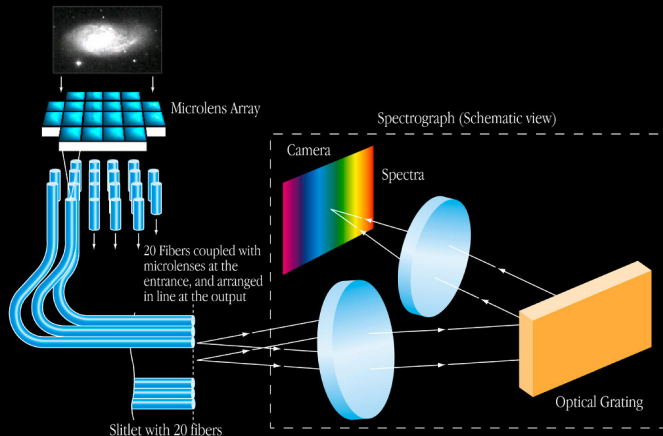


# Integral field spectrograph

- ▶ Current implementations, like MUSE at ESO, feature
  - ▶ lenslet arrays, which relay the image to an
  - ▶ optical fiber bundle, used to
  - ▶ rearrange the image along the spectrograph slit, where
  - ▶ it is detected in long-slit mode, and
  - ▶ reconstructed via a computer.

See the HII region long form lesson to see what MUSE can do.

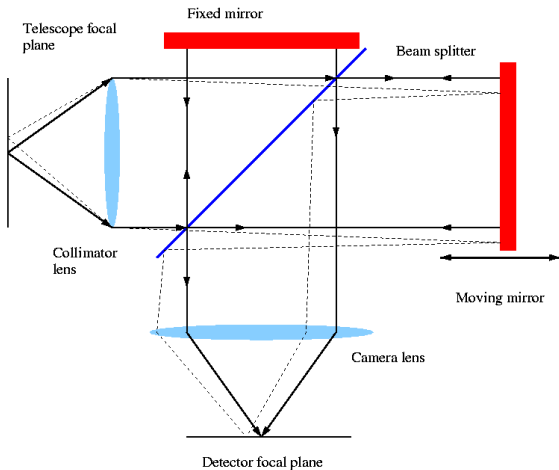
- ▶ No light is lost at the list due to seeing variation, tracking errors, etc. Thus, it is also great for precision wideband spectra of point sources (i.e. exoplanets).



# Imaging Michelson interferometer

**Ideally**, the best of all: full field imaging and high resolution spectra in every pixel.

- ▶ Input light is divided with a beamsplitter.
- ▶ Half of the light is reflected from a stationary mirror, while the other half is reflected off of a mirror that can move.
- ▶ The light joins up again at the beamsplitter, but half of it has an extra path-length difference from the other half.
- ▶ This light is focused on the detector array.

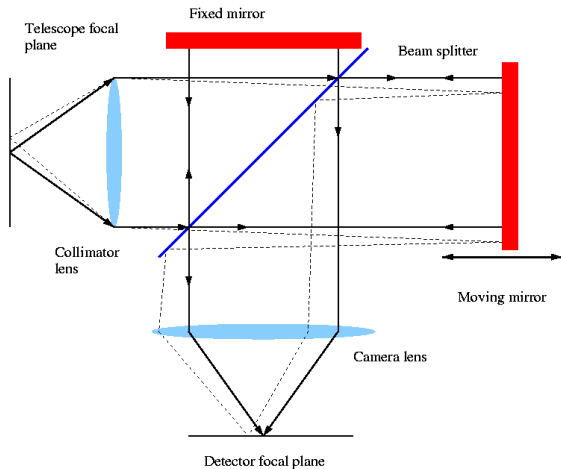


*J. Graham*

# Imaging Michelson interferometer

- ▶ The movable mirror is repeatedly scanned over a fixed range.
- ▶ The array signal (in each pixel) is recorded during the scan, where the range is finely sampled.
- ▶ By averaging these scan records and taking the Fourier-transform of the result, you get a complete spectrum at every pixel.
  - ▶ The wavelength coverage is determined by the sampling rate.
  - ▶ The resolution is determined by the maximum path-length difference:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{4d}$$

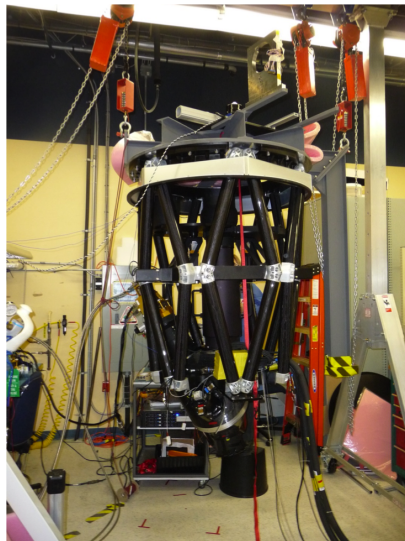


*J. Graham*

# Imaging Michelson interferometer

## Disadvantages:

- ▶ It is much more complicated than the other options, and there are many more challenging high-precision control systems that are necessary (so very expensive).
- ▶ It is vulnerable to additional sources of noise and systematic error.
- ▶ As a result, there are not many that currently exist. One example is SITELLE at the 4-m Canada-France-Hawaii telescope, which covers the entire visible band (in six chunks) and achieves  $\Delta\lambda/\lambda \sim 10^{-4}$  in a  $2048 \times 2048$  pixel, 11-arcmin square field.



SITELLE

# Spectral lines of atoms and ions at visible wavelengths

In this class, we will be concerned with electronic transitions of atoms and ions. They comprise the visible emission from HII regions, planetary nebulae, supernova remnants, and HH objects.

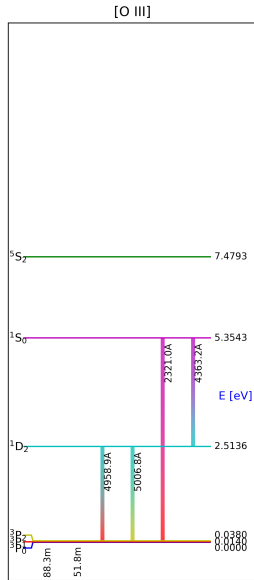
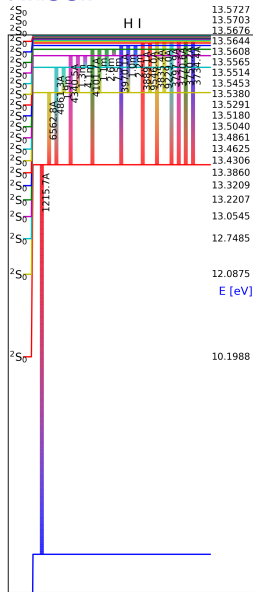
- ▶ Recombination lines of hydrogen (HI)
  - ▶ Electric dipole transitions, after recombination in a high- $n$  state
- ▶ Forbidden lines of other elements, like O, O<sup>+</sup>, O<sup>++</sup>, or S<sup>+</sup>...
- ▶ Remember, the forbidden-line spectra are referred to as [OI], [OII], [OIII], and [SII], respectively.

Z	Name	Ionization potential [eV]				
		0	+	++	+++	++++
1	H	13.6				
2	He	24.6	54.5			
3	Li	5.4	75.6	122.5		
4	Be	9.3	18.2	153.9	217.7	
5	B	8.3	25.2	37.9	259.4	340.2
6	C	11.3	24.4	47.9	64.5	392.1
7	N	14.5	29.6	47.4	77.5	97.9
8	O	13.6	35.1	54.9	77.4	113.9
9	F	17.4	35.0	62.7	87.1	114.2
10	Ne	21.6	41.0	62.5	97.1	126.2
11	Na	5.1	47.3	71.6	98.9	138.4
12	Mg	7.6	15.0	80.1	109.3	141.3
13	Al	6.0	18.8	28.4	120.0	153.8
14	Si	8.2	16.3	33.5	45.1	166.8
15	P	10.5	19.8	30.2	51.4	65.0
16	S	10.4	23.3	34.8	47.2	72.6
17	Cl	13.0	23.8	39.6	53.5	67.8
18	Ar	15.8	27.6	40.7	59.8	75.0
19	K	4.3	31.6	45.8	60.9	82.7
20	Ca	6.1	11.9	50.9	67.3	84.5
21	Sc	6.6	12.8	24.8	73.5	91.7
22	Ti	6.8	13.6	27.5	43.3	99.3
23	V	6.7	14.7	29.3	46.7	65.3
24	Cr	6.8	16.5	31.0	49.2	69.5
25	Mn	7.4	15.6	33.7	51.2	72.4
26	Fe	7.9	16.2	30.7	54.8	75.0
27	Co	7.9	17.1	33.5	51.3	79.5
28	Ni	7.6	18.2	35.2	54.9	76.1

# The ions in our filter wheel

Lowest-energy states of the ground electronic configurations of  $O^{++}$  and  $S^+$  compared to the states of H.

- ▶ Note the scale difference between the different ions.





## Step 1 of analysis (short form)

Essentially, the main point of the HII region and HH objects projects is to make images of the abundance ratios  $\chi_{\text{O}^{++}} = n(\text{O}^{++})/n(\text{H})$  and  $\chi_{\text{S}^+} = n(\text{S}^+)/n(\text{H})$ .

- ▶ Answers will be very different for the two classes of objects, which you should seek to explain.
- ▶ The intensity of an optically-thin  $j$  to  $i$  hydrogen recombination line is given, apart from extinction, by

$$I_{ji} = \frac{hc}{4\pi\lambda_{ji}} \alpha_{ji} \int n_e n_p ds$$

where

$I_{ji}$  is the intensity in erg/s/cm<sup>2</sup>/ster (which you measure)

$\lambda_{ji}$  is the wavelength

$\alpha_{ji}(T)$  is the effective recombination coefficient, in cm<sup>3</sup>/s, calculated quantum-mechanically

$n_e, n_p$  are number per unit volume of electrons and protons

and the integral is over the distance  $s$  along the line of sight through the nebula.

## Step 1 of analysis (short form)

- ▶ Our recombination lines,  $H\alpha$  ( $j = 3, i = 2$ ) and  $H\beta$  ( $j = 4, i = 2$ ), can safely be taken to be optically thin.
- ▶ The [OIII] and [SII] lines are not recombination lines; they are collisionally excited.
  - ▶ The electrons collide with these ions in their ground state, transferring some of their kinetic energy to the ion and leaving them in the upper state of the line.
  - ▶ Eventually, the ion radiates a photon, or collides with another electron, to return to the ground state.
  - ▶ These lines can also be taken to be optically thin.

## Step 1 of analysis (short form)

- ▶ We detect the photons that are radiated. The optically-thin intensity of the  $j$  to  $i$  transition is

$$I_{ji} = \frac{hc}{4\pi\lambda_{ji}} A_{ji} \int n_j ds = \frac{hc}{4\pi\lambda_{ji}} A_{ji} \int f_j \chi n_p ds$$

where

$A_{ji}$  is the spontaneous radiation rate (Einstein  $A$  coefficient) in  $s^{-1}$

$n_j$  is the number density of the ion in state  $j$

$f_j$  is the fraction of the ion's population in state  $j$

$\chi$  is the ratio of the ion's number density to that of hydrogen

Other terms are as before, and again the integral is over the distance  $s$  along the line of sight through the nebula.

- ▶ We know almost none of the properties of the nebula *a priori*: we know only that hydrogen densities more than about  $n_p = 10^4 \text{ cm}^{-3}$  are very rare outside of neutral molecular clouds.
- ▶ This should be compared to the **critical density** of each forbidden line: the density at which the rates of radiative and collisional decay of the upper state are equal.

## Step 1 of analysis (short form)

- ▶ If the actual density is much smaller than the critical density, the fraction of the ions in the upper state is given by

$$f_j = \frac{n_e \gamma_{ij}}{A_{ji}}$$

where  $\gamma_{ij}(T)$  is the collisional excitation rate coefficient in  $\text{cm}^3/\text{s}$  of state  $j$ .  $\gamma_{ij}$  is also calculated quantum-mechanically.

- ▶ This is generally a good approximation for visible forbidden lines. In this case, the intensity ratio of a forbidden line and a hydrogen recombination line determines the relative abundance  $\chi$ . For example, if  $\chi$  is uniform along the line of sight,

$$I_{\text{H}\alpha} = \frac{hc}{4\pi\lambda_{\text{H}\alpha}} \alpha_{\text{H}\alpha} \int n_e n_p ds \quad I_{[\text{OIII}]} = \frac{hc}{4\pi\lambda_{[\text{OIII}]}} A_{ji} \int \frac{n_e \gamma_{[\text{OIII}]}}{A_{ji}} \chi_{\text{O}^{++}} n_p ds$$

$$\chi_{\text{O}^{++}} = \frac{\lambda_{[\text{OIII}]}}{\lambda_{\text{H}\alpha}} \frac{\alpha_{\text{H}\alpha}}{\gamma_{[\text{OIII}]}} \frac{I_{[\text{OIII}]}}{I_{\text{H}\alpha}}$$

## Step 1 of analysis (short form)

- ▶ The only other nuance is that our [SII] filter includes two [SII] lines of similar strength that we cannot resolve.
- ▶ But, this just adds one more term proportional to the  $S^+$  abundance:

$$I_{H\alpha} = \frac{hc}{4\pi\lambda_{H\alpha}} \alpha_{H\alpha} \int n_e n_p ds$$

$$I_{[SII]} = \frac{hc}{4\pi\lambda_{[SII]1}} \int n_e \gamma_{[SII]1} \chi_{S^+} n_p ds + \frac{hc}{4\pi\lambda_{[SII]2}} \int n_e \gamma_{[SII]2} \chi_{S^+} n_p ds$$

$$\chi_{S^+} = \left( \frac{\gamma_{[SII]1}}{\lambda_{[SII]1}} + \frac{\gamma_{[SII]2}}{\lambda_{[SII]2}} \right)^{-1} \frac{\alpha_{H\alpha}}{\lambda_{H\alpha}} \frac{I_{[SII]}}{I_{H\alpha}}$$

## Step 1 of analysis (short form)

- ▶ The numbers that you need are

$$\gamma_{[\text{SII}]1} = 6.514 \times 10^{-9} \text{ cm}^3/\text{s}$$

$$\gamma_{[\text{SII}]2} = 9.702 \times 10^{-9} \text{ cm}^3/\text{s}$$

$$\gamma_{[\text{OIII}]} = 1.133 \times 10^{-9} \text{ cm}^3/\text{s}$$

$$\alpha_{\text{H}\alpha} = 8.643 \times 10^{-14} \text{ cm}^3/\text{s}$$

- ▶ The relative abundance in a typical HII region:

$$\chi_{\text{O}} = (3.3 \pm 0.5) \times 10^{-4} \quad \chi_{\text{S}} = (1.0 \pm 0.1) \times 10^{-5}$$

- ▶ For more details, see the Long Form.