Spectra

1. Basics & Nomenclature

Spectra of objects can be determined in a number of ways, through refraction, diffraction, or through energy-sensitive devices (most commonly in the X-rays). Here we concentrate on the issues most relevant to diffraction grating spectra, though many of these issues are also relevant in other contexts.

Typically, spectra are obtained by putting a dispersive element in the collimated beam. Although prisms can and have been used at the objective pupil, more typically the dispersing element is at a pupil beyond the focus. In addition to providing a smaller area for the dispersing element to cover, this allows the focal plane to be used to remove light not associated with the object or object of interest. Slit spectrographs put a slit (or many slits) in this focal plane, recollimate the diverging beam, disperse it, and then refocus it on a new focal plane. Fiber spectrographs use optical fibers in the focal plane and then align the fiber outputs in a convenient manner with respect to the detectors.

Diffraction gratings consist of optical elements ruled in some manner with a set of closely spaced apertures. At any given wavelength, light coming through the grating will be diffracted. The majority of energy passes straight through in the 0th order mode, but diffraction causes additional modes at angles perpendicular to the ruling. The location of the 1st and greater order modes depends on wavelength, meaning the higher-order modes yield spectra, with larger dispersion but a smaller fraction of the incoming energy at higher order modes. Traditional diffraction gratings were usually ruled metal or mirrors, often mated to a prism (a configuration known as a *grism*) to reorient the desired mode along a convenient path. Modern gratings are usually volume-phase holographic gratings, created within a substrate through holographic techniques. With greater control over the grating geometry, these gratings typically result in optics with higher throughput by avoiding occlusion along the geometric optics light path.

Spectra can be described as having a characteristic resolution. The raw spectrum is usually detected in a two-dimensional image, and the spectrum appears along a somewhat curved line, known as the *trace*, traversing the image along the dispersion direction. The resolution parallel to the dispersion direction is known as the *line spread function*, whereas the resolution perpendicular to the dispersion direction is known as the *point spread function*, in analogy to an image.

For slit spectra, the point spread function is determined largely by the seeing and telescope PSF; the actual profile of the spectrum perpendicular to the trace is the image of the object convolved with the PSF. For fiber spectra, the light is usually sufficiently scrambled that the width of the PSF is determined by the size of the fiber, as reimaged by the camera.

The line spread function is charactered by the resolution $R = \lambda/\Delta\lambda$, where $\Delta\lambda$ is usually the

FWHM of the LSF (but not always). It is determined by the size of the fiber and the dispersion power of the grating. For exposures more than a few minutes, any flexure of the spectrograph over the course of the exposure may also cause blurring in the LSF (or PSF).

The raw spectra need to be extracted and calibrated. The *extraction* involves inferring a signal as a function of position on the trace, to create a one-dimensional spectrum. The position in pixels needs to be converted to wavelength; the relationship between the two is usually inferred by injecting a signal into the spectrograph, often sourced by an *arc lamp* which emits light at discrete lines associated with ionized inert gases (He, Ne, Ar, etc).

The signal needs to be converted to flux units. If we assume the detector is bias-subtracted as if it were an image, the signal in the trace can be modeled as:

$$\mathrm{DN}(x) = [f(\lambda(x)) + f_{\mathrm{sky}}(\lambda(x))] \times F(x) \times T(\lambda) \tag{1}$$

The quantity $F(x)$, the *flat*, characterizes the effects of the detector response and is typically determined by injecting light from a flat-field lamp, which has a broad spectrum; in fact, only small-scale features are usually retained from the flat-field for reasons that will soon be clear.

The quantity $T(\lambda)$ characterizes the throughput as a function of wavelength, and is affected by the atmospheric transmission, how much of the light enters the spectroscopic aperture at any given wavelength, and the throughput of the optics, as well as any remaining dependence of efficiency on wavelength on scales larger than those probed by the flat. It must be determined in part by observing standard stars whose true spectra are assumed, either through additional slits or fibers at the same time as the objects of interest, or through the same slits or fibers at slightly different times. Either approach requires accounting for the resulting slight differences in the observations.

The sky signal $f_{\mathrm{sky}}(\lambda)$ also needs to be removed. In the case of slit observations, the sky can be estimated from the outer parts of the slit, which contain little object flux. In the case of fiber observations, the sky needs to be estimated from other nearby fibers. Because the fiber varies with position and time on the sky, this can be uncertain.

2. Commentary

In ground-based spectroscopy it is extremely important to pay attention to the chromatic atmospheric refraction. This effect can lead to different amounts of light getting through fiber or slit as a function of wavelength, because the image in the telescope focal plane is a function of wavelength. These differences lead to both a variation in throughput and potential loss of signal-to-noise, and also may make the spectrum hard to calibrate (if the standards used are not under the same conditions). Slit spectra are often arranged so that the slit is parallel to the parallactic direction to minimize this effect, but there is no such mitigation for fibers. Atmospheric dispersion correctors consisting of crossed prisms can be used to reduce this effect, but they need to act in a pupil so are large and expensive.

In practice, the difficulty in sky subtraction is almost entirely due to the LSF modeling. Typically the issue arises because there are strong lines that need to be subtracted, and so the LSF model needs to be very good to be accurate enough. In addition, the sky can have a different LSF than the object, since there are slit-filling issues or due to imperfections in the extraction method.

3. Key References

- *Design and Construction of Large Telescopes*, Bely (2003)
- *Astrophysical Techniques*, Kitchin (2009)

4. Order-of-magnitude Exercises

1. Assuming the centroid accuracy is related to R and S/N ratio in a similar way for optical spectra of single emission lines as for point sources in an image, for an unresolved line with $S/N \sim 10$ in its total flux, how high R do you have to be to determine a Doppler velocity to 10 km s^{-1} precision? How would a redshift determination using a full optical spectrum (i.e. using many lines) change the precision of the determination qualitatively? How does dependence of the velocity precision on R differ qualitatively for absorption lines?

5. Numerics and Data Exercises

1. Find an SDSS spectrum of a galaxy and sky fiber from the same plate of the BOSS survey. Plot the sky and the object spectrum.
2. Find an arc spectrum from the BOSS survey, and a corresponding sky spectrum taken during the same calibration-exposure sequence. You will need to use the `spPlan2d` files to figure out which `spCframe` files to use. Find at least one pair of sky and arc lines, each of which is bright and isolated from other lines. Estimate the FWHM of the LSF from each and compare them.

REFERENCES

Bely, P. Y. 2003, The Design and Construction of Large Optical Telescopes

Kitchin, C. R. 2009, Astrophysical Techniques, Fifth Edition

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