THE BAADER SPECTROSCOPE/SPECTROGRAPH

by Stephen J. Edberg

Getting Started

Your Baader Spectroscope/Spectrograph will open a new window on the universe for you. With it you will gain a greater understanding of how the universe is made.

The spectroscope consists of several parts:

1. The diffraction grating is the heart of the Instrument. NEVER touch its surfaces. It should always be stored in its protective case when not in use and should only be cleaned with air from a can or squeeze bulb (but not from your mouth).

2. A specially designed and mounted cylindrical lens that snaps into its holder will turn the narrow, line-like spectra of stars into bands of color. An eyeshade and a plastic adapter (cut a hole in the end to use it) to help fit the cylindrical lens to your eyepieces are also included.

3. A grating holder in which the grating cell is screwed. In the other end an eyepiece or camera T-ring (or both) can be attached.

You have to supply a telescope that accepts 1.25 inch eyepieces and one or more eyepieces. If you want to photograph spectra you will also need a T-ring for your Single lens reflex (SLR) camera and the camera body itself. (If you don't own an SLR you can still attempt photography as described later.)

If you are anxious to get started follow the steps below. We encourage you, though, to read through this manual to learn how your spectroscope/spectrograph works, how to set it up, and what projects to try.

1. Carefully remove the diffraction grating from its protective case and screw it into the holder (be careful not to cross thread the grating and holder).

2. Insert a low power eyepiece in the other end of the holder and place the whole assembly in the focuser of the telescope.

3. Locate a bright blue star such as Vega (Alpha Lyrae) or Sirius (Alpha Canis Majoris) in the telescope. Notice the star and its spectra, surrounding it on both sides. Focus the spectroscope assembly so the star is a point and the spectra are lines. Center on the brightest spectrum.

4. Place the cylindrical lens over the, eyepiece and rotate it until the star image is a line perpendicular to the brightest spectrum, which now appears as a colored band, stretching from violet to red, like a rainbow. Look carefully for dark lines (perpendicular to the spectrum and paralleling the star's linear image) in the spectrum: the narrow lines of missing color can tell you the surface temperature and composition of the star, among other characteristics. Try higher powers to find the best magnification for spectrum visibility.

Background

Spectroscopy is one of the most powerful methods of investigating celestial bodies, allowing astronomers to determine the composition, temperature, pressure, rotation, magnetic field strength and motion of these objects. To do spectroscopy one must use a dispersing element - a prism or diffraction grating to break down light into its component wavelengths (colors).

The Baader spectroscope uses a diffraction grating to disperse the light. A laser holography System was used to make it. The grating has a series of parallel lines or grooves on it, several hundred to the millimeter, which act to spread the light into a rainbow of color, called a spectrum (plural: spectra). The spread, or dispersion, depends on the number of grooves/mm. It is nearly constant, unlike the dispersion of a prism, throughout the spectrum from red to violet. A grating also transmits all colors of light equally well, unlike a prism whose glass absorbs more violet light than red light.

The disadvantages of a grating are that the grooves are delicate and easily damaged and that it produces a large (actually infinite) number of individual spectra, called orders, which make any particular order less intense than if all the light were going into it alone. A solution to this problem is found by adjusting the groove shape. This allows most of the light to be directed into one order and is called "blazing" the grating.

Orders are numbered increasing outward on both sides from the zero order (which is the direct image of the object). They generally get fainter with increasing order number, except for the blazed order which is brightest by design. Starting with the second order and increasing, the spectral orders have greater and greater overlaps on each other. You can see several orders by looking at a bright light source (not the Sun!) through the grating and slowly turning away from the source.

Any object that emits light of its own generates a characteristic spectrum. There are three types of spectra:

1. A continuous spectrum is emitted by incandescent solids, liquids, or high density gases. A tungsten light bulb's filament emits such a spectrum, which is a band of color with the colors merging smoothly from one to another.

2. An emission spectrum is emitted by a hot gas. Bluish (mercury vapor) and golden (low pressure sodium) street lights (not the pinkish high pressure sodium type) and orange neon lights generate an emission spectrum, in which you can see only certain, narrow colors. In the sky planetary nebulae, most diffuse nebulae, and the aurora have emission spectra.

3. An absorption spectrum is produced when a cool gas (or certain other materials) is between a source of a continuous spectrum and the observer. The cool gas absorbs just the wavelengths it would emit if it were hot (this is one of Kirchhoff’s laws) and a continuous spectrum is seen with dark Spaces where colors are missing. The spectra of most stars are the absorption type.

In addition, combinations of these spectrum types can be observed.

Often you hear spectral lines mentioned. These are simply the specific wavelengths (colors) emitted/absorbed by a particular atom or molecule. Each chemical element and compound has its own characteristic set of spectral lines that is as personal as fingerprints are for people. Thus we can determine the composition of light emitting objects simply by looking at their spectra and matching them to known patterns from various elements and compounds.

"Lines" is a reference to the fact that a narrow slit is often used in a laboratory or with a large telescope's spectroscope or spectrograph to improve its resolution. In a slit spectroscope individual colors emitted by a hot gas or a spark appear as lines (hence the name) in the emission spectrum, oriented perpendicular to the dispersion. A look at a mercury streetlight through a grating will show multiple images of the light (and its fixture), each in its own distinctive color: the colors are the spectral lines of mercury, but they appear in the shape of the lamp fixture, not as line segments, because no slit was used.

Your eyes are sensitive to violet wavelengths as short as 400nm (nanometers; a nanometer is a billionth of a meter) and red wavelengths as long as 700nm, depending on the light's intensity. Most photographic emulsions are sensitive to wavelengths considerably shorter than 400nm and to 600-700nm on the red end. (Infrared sensitive emulsions may be sensitive as far as 1100nm.)

Using Your Spectroscope/Spectrograph

In this section we describe how to set up and use your Instrument. Your spectroscope/spectrograph is easy to use in either mode. Specific observing projects are suggested in the next section.

First, carefully mount the diffraction grating to the grating holder. Next, insert an eyepiece (low power is best) into the other end of the grating holder. Tighten the thumbscrew to look the eyepiece in. (Note that the second thumbscrew is for photography and locks the outer extension tube at the desired length.) Insert the spectroscope assembly into the telescope's focuser and aim at a bright star.

Focus the spectroscope and point the telescope so that the zero order direct point-like image and the blazed (brightest) first order linear spectrum are centered in the field of view. Now fit the cylindrical lens (and eyeshade, if desired) to the eyepiece. Orient the cylindrical lens so that the zero order image now appears as a line perpendicular to the first order spectrum, which appears as a ribbon of color. Refocus slightly, if necessary, to sharpen the spectral lines; this may make the zero order image bulge in the middle.

Now you can study the spectra of any stars you want by re-aiming the telescope. Just look for absorption lines (and for a few stars, emission lines in the spectrum). If you suspect an emission line in a spectrum, rotate the spectroscope slightly: if the emission line moves with the spectrum it is a true emission line and not the zero order image of a star underlying a first order spectrum. You can also change magnifications by changing eyepieces, refocusing and replacing the cylindrical lens. At higher powers the aiming may need to be corrected and the image brightness will decrease.

As you become more familiar with your instrument, you may prefer to find your target first and then use the spectroscope assembly. Since the spectroscope retains the field of view of the eyepiece, you don't need to leave it in to do your aiming, and with faint targets it is definitely easier to find them first without the spectroscope.

Six inch and larger telescopes will allow the study of the spectra of brighter nebulae and galaxies; for extended, non-stellar objects do not use the cylindrical lens. Gaseous nebulae, especially planetary nebulae, will not look significantly different when your spectroscope is used to observe them, except perhaps at high magnifications. The emission lines in these nebulae are closely spaced and almost overlap each other so the nebular spectrum will not look much different from the object itself. Nearby stars, however, will be spread into their spectra. At high powers you may be able to resolve the nebular spectral images, especially if the nebula is small.

The astronomical seeing must be good for your spectroscope/spectrograph to work well. Large, blurry star Images will blur spectral lines into the nearby continuous spectrum (called the continuum) , making spectral studies difficult. Because the bright planets are extended sources (as is a star observed under conditions of poor seeing), viewing the Sun's spectral lines as reflected by the planet will also prove disappointing. (This is not the case, though, when making an objective grating photograph as described below. In that Situation the planet will be star-like with short focal length camera lenses and the Sun's spectral lines can be photographed.)

To photograph spectra there are two very simple spectrograph designs you can use. The cylindrical lens is not needed. Be aware that chromatic aberration in your lenses may become very evident as you photograph spectra.

The first method, called OBJECTIVE GRATTNG SPECTROSCOPY, places the grating in front of any camera lens of any SLR or non-SLR camera.
You will need to make an adapter out of cardboard, balsa wood, metal, or plastic that will hold the grating in front of your camera lens. Alternatively, you may find an adapter at a camera store that will allow the T-threads of the grating holder to attach to the threads on your camera lens. In either case, expect some loss of field of view and vignetting, since the grating is probably smaller than your lens. A stray light shade (lens shade) surrounding the grating may also prove useful.

For bright stars (magnitude 1 or 2) five minutes of star trails taken with the camera on a tripod should be sufficient to record their spectra on fast (200 - 400 ISO) color or black & white film. Focus at infinity with the lens aperture wide open. The direction of dispersion must be perpendicular to the direction of trailing. (In other words, the spectrum should be aligned North-South in the sky so the apparent East-to-West drift of stars caused by Earth's rotation widens the spectra.) Use a cable release to minimize shutter opening/closing Vibration.

Fainter stars will be recorded if guided exposures on an equatorial mount are made. Again, the dispersion should be in the direction of declination. Some widening of the spectrum is necessary to see spectral lines; just vary the drive rate a little.

Besides stars, the spectra of large, bright nebulae, comets, meteors, the Sun's corona during eclipses, and lightning can also be recorded using an objective grating. The efficiency of the grating, film speed, f/number of the optical System, and width of the spectrum perpendicular to the dispersion (a function of declination) limits the stellar magnitude attainable with this system. Sky brightness also plays a part.

Wavelengths of spectral lines may be identified by using the formula:

$$Wavelength\,(in\ mm) = \frac{d \times L}{n \times \sqrt{[L^2 + F^2]}}$$

Where d = 1 / (# of grooves/mm) of the grating (this grating has ??? grooves/mm);
n = the order number of the spectrum used for measurement (you can see and photograph higher order spectra if you want, and get higher dispersion at the same time);
L = the distance on the negative or positive from the zero order image to the spectral line in mm;
F = the focal length of the lens used in mm.

Beware of a zero order star image mimicking an emission line in another star’s spectrum.

With NONOBJECTIVE SPECTROSCOPY the grating is placed between any telescope objective (used as a light collector) and a camera body to hold the film. The camera lens is unnecessary, as the telescope acts to collect and focus light which is dispersed on the way to the film plane. Attach a T-ring for your camera to the grating + grating holder and that assembly to your camera body to make your spectrograph. (You may need to rotate the T-ring’s internal ring so that spectra parallel the long side of the camera’s rectangular field of view.) The sleeve on the grating holder allows you to vary the length of the spectrum on the film, depending on how extended the sleeve is (more extension lengthens the spectrum). Insert the grating end of the spectrograph into the telescope’s focuser to complete the set-up.

It is important to focus on the spectrum (use a bright star near the target) when using this system since the grating introduces coma, astigmatism, and field curvature. (Non-SLR users can photograph spectra using the afocal method of astrophotography. Insert a low power eyepiece between the grating and camera lens and focus the spectrum made by the telescope – grating – eyepiece for your eye. Set the camera lens to infinity focus and the aperture wide open. Place it close to and in line with the eyepiece. Note that aiming is a problem since the view through the camera is not available as it is with an SLR.)

The nonobjective technique has been used with great success with telescopes as large as four meters for the detection of faint emission line sources such as quasars. Spectral lines may be identified according to the formula:

$$Wavelength\,(in\ mm) = \frac{d \times L}{n \times \sqrt{[L^2 + D^2]}}$$

where D = the distance from the grating surface to the film plane in mm. Crowding is not generally a problem with this System since the field of view is that of the telescope. A larger objective makes this method more efficient. A low focal ratio (f/ number) reduces the spectral resolution of this method. In terms of image brightness, however, for stellar sources the focal ratio is unimportant though it will matter for an extended object such as a planetary nebula.

Terrestrial and Celestial Projects

Your Baader spectroscope can open a whole new fascinating field for you. With the Instrument in hand, personal discoveries need only a glance at a source of light. We offer here a few projects for you.

1. Using the grating only (or grating + grating holder for convenient handling), look at various lights around your home. Note the spectrum types as you look at point or line sources (or make a cardboard mask to cover larger lights; you can use a cardboard tube to mount the grating in one end and a pair of razor blades edge to edge to make a slit for a convenient hand spectroscope – look through the grating at the razor blade slit while aiming at a light source). Watch the spectrum change as you change the dimmer setting on a tungsten light (hint: watch the blue end). Note the continuous + emission spectrum of fluorescent lights (a misnomer: they are phosphorescent lights because a phosphor lining the tube produces the continuous spectrum). Remember the relative positions and colors of the emission lines and try to identify their chemical source (see Project 3 below). What kind of spectrum does a candle flame have? What happens if you drop table salt in the flame? Do the spectral lines in the salted flame match any in street lights (Project 3)?

2. Using a tungsten light bulb as a source of light look through colored glass or plastic with your spectroscope. Note which colors are visible in the spectrum of each color filter. Look at the colors reflected by various colored objects (you may need a more intense light source).

3. Look at street lights and advertising sign lights with your spectroscope. Street lights are usually one of the types described below:
   a) Tungsten, looking off-white overall and yielding a continuous spectrum;
   b) Mercury vapor, looking bluish overall and yielding an emission spectrum;
   c) High pressure sodium. looking pinkish overall and yielding a continuous, absorption, and emission spectrum (!);
   d) Low pressure sodium, looking golden overall and yielding an emission spectrum.

   Do any of these spectra match a fluorescent light? Can you understand why the lights show the overall colors that they do? Photograph streetlight spectra (bracket your exposures). Does the photograph show more spectral lines than your eye sees? If so, on the red or blue end of the spectrum? Advertising lights and neon night lights may show some spectra you haven't seen before (and some you have!).

4. Photograph a continuous spectrum front a point or line source using different color and black & white films. Even panchromatic films show a decrease in sensitivity in the green. Color films, when underexposed, will show all three emulsion layers, each layer being one color throughout its extent. The three colors, blue, green and red, will be separated by dark Spaces where sensitivity is low. Sufficient exposure is necessary to fill the space between blue and green with aqua and the space between green and red with yellow and orange. By lining up the zero order images you can compare the spectral sensitivities of various emulsions assuming the exposures (the amount of light falling on the film, accounting for the differences in film speed) are equivalent. Which emulsions have the best red sensitivity? You can also do the color filter test in Project 2 photographically. Photograph nearby and distant streetlights.

5. Observe the spectral differences between stars. To begin with, compare the blue end of the spectra of bluish and reddish stars. Stellar spectra studied visually or photographically will easily show the differences between stars and allow for their classification:

   0 and B stars have almost featureless spectra.

   A stars have strong hydrogen absorption lines.

   F, G, and K stars have weakening hydrogen lines and stronger metal lines.

   M stars continue to show metal absorption lines as well as molecular absorption bands.

   R, N, and S stars have molecular bands different from those in M stars.

Emission lines will appear in Wolf-Rayet and other emission line stars and novae as well as in planetary and most diffuse nebulae. Besides showing the lines used in the stellar classification scheme, the shift in color with type becomes obvious and can be recorded permanently with a photograph, even with black & white film. This is seen as the shift of the most exposed wavelengths farther and farther from the zero order position (i.e., from blue to red) as the stellar type ranges from 0 to M. However, do not confuse the variation of film sensitivity across the spectrum with the shift in color with stellar spectral type (see Project 4).

6. With a 6" or larger telescope compare the spectra of a planetary nebula, a diffuse nebula, a reflection nebula, and a supernova remnant. See (and if possible, photograph) the differences in the spectra of these apparently similar objects. What kind of spectrum does a galaxy present?

References

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SPECTRAL CLASSES

CLASS	DESCRIPTION	BRIGHT EXAMPLE
STARS		
0	Weak absorption lines of helium and hydrogen.	Zeta Puppis
B	Stronger absorption lines of helium and hydrogen.	Rigel, Spica
A	Hydrogen lines strong. No helium lines.	Sirius, Vega
F	Weaker hydrogen, stronger ionized calcium And other metals	Procyon
G	Strong calcium and other metals, weak hydrogen.	Sun (planets), Capella
K	Many metal lines.	Arcturus
M	Many metal lines and molecular bands of titanium oxide.	Antares, Betelgeuse
R	Weak molecular carbon bands	S Camelopardi
N	Carbon bands present.	Y Canum Venaticorum
S	Similar to M stars but zirconium	R Cygni
	Oxide replaces titanium oxide.	
W	Emission lines present.	Gamma Velorum
NEBULAE		
Planetary	Shell of gas excited by a hot white dwarf star	Ring Nebula (M 57)
Diffuse (Emission)	Chaotic cloud of gas excited by hot, probably newborn stars.	Orion Nebula (M 42)
Reflection	Caotic dust cloud illuminated by one or more stars	M 78
Supernova Remnant	Chaotic gas shell formed by the explosion of a star	Crab Nebula (M 1)

USEFUL WAVELENGTHS

Wavelengths are given in nanometers, nm. A nanometer is a billionth of a meter = a millionth of a millimeter = 10 Angstroms (symbol D).

ELEMENTS:

Hydrogen	Alpha	656.3	Mercury	579.1
	Beta	486.1		577.0
	Gamma	434.0		546.1
	Delta	410.2		435.8
	Epsilon	397.0		407.8
				404.7
Sodium	D1	589.6		
	D2	589.0		

OFTEN SEEN IN ABSORPTION IN STARS:

Hydrogen 656.3, 486.1, 434.0, 410.2

Calcium 422.7

Calcium II (ionized) 396.8, 393.4

Magnesium 518.4, 517.3, 516.9

Sodium 589.6, 589.0

Iron and molecules of titanium oxide, zirconium oxide, carbon, and cyanogen all have spectral lines too numerous to list here.

OFTEN SEEN IN EMISSION IN NEBULAE:

Hydrogen 656.3, 486.1, 434.0, 410.2

Oxygen III (ionized) 500.7, 495.9

Nitrogen II (ionized) 658.4, 654.8

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