PART 3: METEOR SPECTRA

1. A brief historical review

The first photographic meteor spectrum was obtained accidentally in 1897 by Pickering at the Harvard Observatory. The first successful meteor spectroscopy program was set up in 1904 in Moscow. A quarter of a century later, however, only 8 spectra had been obtained globally. Photography of meteor spectra has never been very popular. As late as 1946, not even 100 spectra had been obtained worldwide. Fortunately, intensive observing programs were eventually set up and by 1961 more than 400 spectra had been recorded. Countries which lead the way in the acquisition of meteor spectrograms were the former U.S.S.R., Canada, the USA, the Czech Republic and Slovakia, where major efforts were made to investigate this aspect of meteor astronomy (Millman, 1980; Millman, 1983).

The introduction of very fast emulsions brought revolutionary progress in all aspects of meteor photography, including meteor spectral studies. The earliest spectra were all taken on blue sensitive plates. After 1932 ortho plates were introduced, which are also sensitive to green and yellow light. Details in the red part of the spectrum were obtained from 1934 onwards. However, infra-red meteor photographs were not obtained until 1952!

Since bright meteors are more likely to occur around the time of meteor stream maxima, this is the most favourable period to devote to capturing meteor spectra. It should come as no surprise to learn that 40% of all meteor spectra are Perseids and 12% Geminids! Indeed, very little spectral information has been gathered concerning minor showers and the sporadic background. The quality of spectra varies widely as well, from very faint ones which show only one line, to cases where 150 and more lines can be measured.

Today the “records” in meteor spectroscopy belong mostly to the Ondřejov Observatory in the Czech Republic: the deepest ever photographed meteor spectrum (down to 20 km height); the maximum number of spectral lines for one spectrum, (over 1000 in the visible region); the greatest dispersion ever for a meteor spectrogram (0.5 nm/mm) and the spectrum of the brightest meteor, that of a fireball of -21^{m} absolute. This is the result of a systematic observing program with long-focal length spectral-grating cameras, which has been going on each clear night since 1960 (Ceplecha, 1991).

2. Classification of meteor spectra

A simple classification system for meteor spectra was introduced by P. M. Millman and was based on the first 24 spectra ever photographed (Millman and McKinley, 1963, p. 747). This classification scheme is based on the identification of the strongest lines in two regions of the spectrum; the orange-green region and the blue-violet region which correspond respectively to 500–600 nm and 350–450 nm.

The four major spectral classes can be defined as follows:

Type Y: the H- and K-lines of Ca II make up the brightest group in the blue-violet.

Type X: when the definition for type Y is not valid, then the D lines of Na I or the lines of Mg I at 518 nm or 383.8 nm respectively are the brightest lines in the orange-green or blue-violet.

Type Z: if the definitions for Type X and Type Y do not hold, then the lines of Fe I or of Cr I are the brightest in the orange-green or the blue-violet regions.

Type W: none of the characteristics of the Types X, Y, or Z occur.

This classification has proved mainly to reflect the velocity of the meteoroid: X belongs to the region of 15 to 20 km/s, Z belongs to the 30 km/s region, Y belongs to the 60 km/s region, and W to meteoroids of unusual composition.
The following elements have been observed in meteor head spectra (Ceplecha, 1967):
(i) neutral atoms (indicated by the "I"): Fe I, Mg I, Na I, Ca I, Mn I, Cr I, Al I, Ni I, Ti I, H I, O I, N I,
(ii) ionized atoms: Ca II, Mg II, Si II, Fe II, N II, O II.
Here "II" stands for single ionization (e.g. Ca^+), a "III" for double ionization (e.g. Ca^{2+}).
There are some additional elements (Co I, Sr I, Sr II, Ba I, Ba II, Si I) which are sometimes identified. In addition, molecular lines and bands can occasionally be identified (N_2, FeO, MgO, CaO, CN, C_2 and others).
A spectrum depends partly upon the composition of the meteoroid and its density, but mostly upon its geocentric velocity (and thus the classification by meteor stream) and also upon its height in the atmosphere.
There is no great difference between the meteor head and wake spectra, if considering element identifications only. As the wake spectra show substantially less excitation than the head spectra, only the lines corresponding to the low-energy states are recorded (Ceplecha, 1967).
Data obtained from spectra are complementary to all other results obtained from meteor photography, such as trajectories and orbital elements, as well as to the visual work from which different stream characteristics can be derived. The spectra, however, provide a unique link to meteorite research. Put together, all this research permits the study of the interrelation and evolution of meteoroids, asteroids and comets.

3. How to build a meteor spectrograph

3.1. The camera and dispersing element

In principle, any camera can be converted into a spectrograph by placing a dispersing element (prism or grating) in front of the lens. More details about the construction of a meteor spectrograph can be found in section 3 of Part 5. Prisms produce one non-linear spectrum. Gratings have the advantage of linear dispersion, but they produce many spectra of different orders overlapping each other. Much of the light from the meteor ends up in the useless zeroth order (the "normal" meteor image with no lines visible). Modern gratings are blazed (meaning the grooves that form the grating lines are constructed to a controlled shape) and this concentrates the majority of the light in a specific order. In general, though, prisms are easier to obtain and of lower price.
We have already mentioned that only lenses with a long focal length (at least 100 mm) are useful for obtaining spectra with a prism. The reason for this is to ensure that a scale sufficient for analysis of the spectrum is achieved. If the dispersion (defined as the spread of the spectral wavelengths of light per unit length on the film) is too small, the lines are not well separated from each other. A large dispersion scale can be achieved using a prism with a large refracting angle, though this also means that the light must pass through a large quantity of glass, leading to light absorption. Alternatively,

we may use a lens of longer focal length. A prism made of glass with a high refractive index n and a refracting angle $\alpha = 25° \ldots 30°$ combined with an $f = 100$ mm lens can produce useful results. Because the camera field must be sufficiently large, a small frame camera is not suitable. An old 6 cm × 9 cm bellows camera or a 9 cm × 12 cm plate camera are very well suited to meteor spectroscopy. Such cameras can often be found for very reasonable prices second-hand.

3.2. The prism and its mounting

The prism employed should have a large deviation angle made of a glass with a high refractive index n. The position and orientation of the prism in front of the camera lens is very important. Care must be taken to ensure that no direct light falls on the lens, which has to be completely covered by the prism. With a deviation angle α of the prism amounting to about 45°, the angle γ between the bottom of the prism and the camera lens should be about 25°. For a smaller angle α, the angle γ decreases.

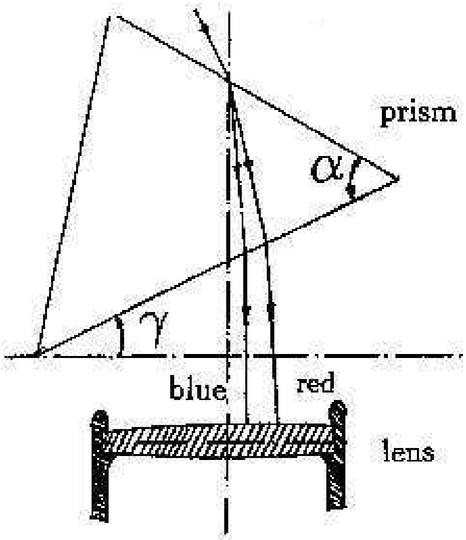

Figure 3-1: Camera with prism — construction principle.

It is convenient to fit the prism and camera into a wooden box; this prevents light reflections on the prism from being projected through the camera lens. This box can also house some heating elements, as experience shows that large prisms are easily covered with dew. An automatic camera for meteor spectroscopy using a prism has described by Degewij (1965).

If a Rowland grating is in use, it is not necessary to use a lens with a long focal length. In this case a small frame camera with a wide angle lens will suffice. The use of a diffraction grating has the advantage that a direct image of the meteor occurs on the film and that higher orders of the spectrum may also be recorded. The disadvantage is that the Rowland grating has to be large enough to cover the entire camera lens, a condition that increases the price of the grating considerably.

The focal length of a lens is normally given for a certain wavelength in the visual range. With a spectrograph we are dispersing the light. Therefore, we obtain parts of an image containing separate wavelengths and consequently different focusing points. Since meteor spectra contain many lines towards the blue part of the spectrum (see the analysis described in section 4 below), it may be useful to focus on the Hydrogen Balmer lines prominent in early type stars or other lines in the blue region. For these wavelengths f is slightly shorter, the lens should be adjusted to a distance of “less than ∞”. Trials with terrestrial light sources may be useful.

3.3. The orientation of the spectrograph

When the spectrograph is aimed at the sky, the orientation of the instrument requires special attention. In many cases this aspect of meteor spectroscopy is completely forgotten or ignored, the consequence being that the very few bright meteors that appear in the camera field are photographed but without a spectrum! Therefore, the spectrograph must be oriented relative to the radiant in such a way that a bright meteor from that radiant will occur perpendicular to the dispersion direction of the spectrograph, in other words, parallel to the long-axis of the grating. Otherwise, the meteor will fill up its own spectral image. An example is presented by Russell (1990). Generally the magnitude threshold for a spectrograph is $2^{\mathrm{m}} \ldots 3^{\mathrm{m}}$ brighter than with the same lens used for direct imaging.

3.4. Double station work and spectroscopic photography

As with an ordinary camera, a spectrograph can be aimed at a given point in the sky. Aiming the camera requires that the optical axis of the camera be fixed (i.e. no clock drives to follow the motion of the sky), so the grating or the prism must be rotated relative to the radiant in such a way as to have any stream meteors travel perpendicular to the dispersion direction. During a double station project of several hours, the position of the prism, or the grating, has to be corrected regularly as the radiant will move relative to the camera position, which is fixed in azimuth and elevation. This should be taken into consideration when building the mounting of the spectrograph.

It is also desirable to add a rotating shutter in front of the spectrograph. In this way, it will be possible to record the spectral lines of the meteor wake in the interruptions on the trail produced by the shutter blades. Otherwise the wake radiation will be inseparable from the head radiation, which makes a detailed spectrum analysis difficult.

3.5. Summary of equipment

The **appropriate equipment** should consist of:

- a camera, preferably with $f = 80 \ldots 120$ mm lens and large film format
- a prism OR a diffraction grating which is well mounted in front of the lens and oriented such that the dispersion of the expected shower meteors is optimal
- a heating system for the whole optics
- a rotating shutter in front of the prism/grating

The **data to be noted** before or during the exposures are:

- focal length of the lens
- data concerning the prism (deflecting angle) or the grating (lines per millimeter), respectively
- start and end of each exposure (use only UT to avoid confusion)
- region of the sky photographed
- orientation of the prism / grating
- film used
- time and magnitude of brighter meteors (if seen)

4. Analysis of meteor spectra

A meteor penetrating into the Earth's atmosphere causes excitation and ionization of atoms and molecules of the air as well as of the atoms of the meteoroid. Different states of excitation correspond to discrete levels of energy. Thus, we will find several monochromatic images of a given meteor (i.e. each spectral line), parallel to each other and of different intensity, while the spectra of stars contain continuous parts and absorption (but rarely emission) lines. Since the direction of travel of the meteor cannot be foreseen, the scale of the wavelength discrimination is unknown, and we have to calibrate it for each photograph separately. Therefore we need a "reference standard". A spectrum of a star of spectral type A will serve this purpose quite well. It contains bright lines of the Balmer series (hydrogen spectrum). In the following paragraphs we briefly describe how to measure and calculate meteor spectra.

All measurements of spectra have to be carried out perpendicular to the monochromatic images of the object (star, meteor). You may measure positions with a measuring microscope or any other device allowing precise coordinate determination in the required direction.

The procedure described below gives the calibration of the dispersion relation, i.e. the amount of dispersion as a function of the wavelength. This has to be done for a given combination of lens and dispersing element (prism or grating). For this, we need an object in the same field providing well defined lines of known wavelength. Such a source can be either a suitable reference star, preferably one of type A, or a terrestrial emission lamp providing enough lines in different parts of the spectrum. For example, a mercury-vapour-lamp, which may be in use for street illumination, will suit this purpose (Fig. 3-2). The high pressure sodium-vapour lamps (orange light) emit light mainly from a doublet line which is broadened by the high pressure and hence does not allow the accurate measurement of line positions.

In any case, you will need a reference table containing the wavelengths and some information about the relative intensity of the spectral lines appearing in the light source used for calibration.

The example given here is from Bakulin (1973, pp. 311-316). The described procedure is somewhat complicated. We mention other options below.

For the procedure we now describe, five reference stars with strong hydrogen lines were chosen.

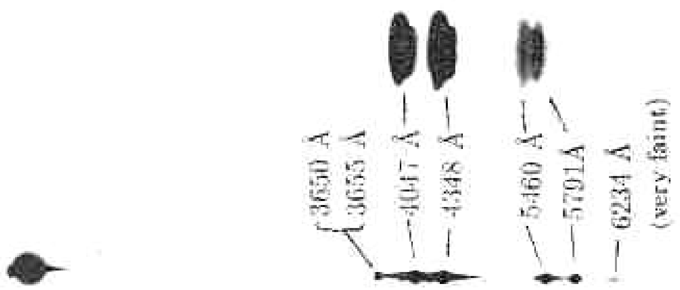

Figure 3-2: Examples for spectra of a mercury-vapour emission lamp obtained with a simple prism of 45° refracting angle and an $f = 50$mm lens (above) and with a transmission grating used with an $f = 135$mm lens (below), respectively. In the first case the camera was moved in vertical direction to get broader lines. The latter example shows the zero-order image (left) as well as the first-order spectrum.

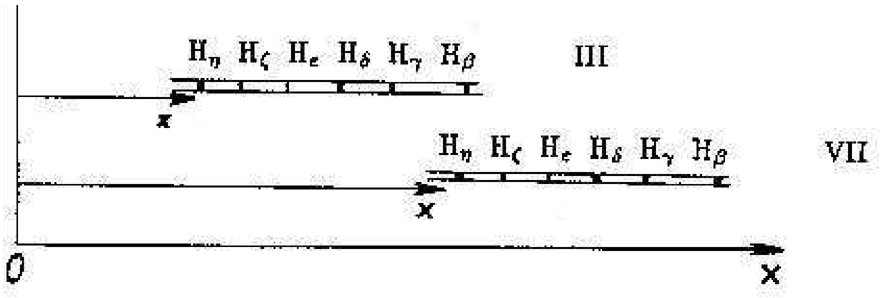

Figure 3-3: Lines in stellar spectra and the coordinate x used for the described measurements. The point 0 may be edge of the image.

Table 3-1: Measurements of the positions of hydrogen lines in five star spectra.

No. of star	III	VII	IX	XIII	XIV
line					
H_β	1.2606	1.6142	3.4276	1.3362	0.7710
H_γ	1.0761	1.4278	3.2488	1.1530	0.5818
H_δ	0.9635	1.3166	3.1393	1.0406	0.4686
H_ε	0.8915	1.2456	3.0669	0.9687	0.3956
H_ζ	0.8432	1.1945	3.0231	0.9218	0.3466
H_η	0.8093	1.1656	3.9897	0.8888	–
coord. of center	1.0070	1.3597	3.1811	1.0841	0.5127

Firstly, in each reference spectrum the coordinates of the main (known) lines are measured in mm from the edge of the image. In order to define the scale for the wavelengths we now calculate the distances of the lines from the centre as shown in Fig. 3-3.

Table 3-2: Definition of the scale as shown in Fig. 3-3.

line	III	VII	IX	XIII	XIV	position $\overline{x}$	wavelength in Å
H_β	0.2536	0.2545	0.2465	0.2521	0.2538	0.2530	4861.6
H_γ	0.0691	0.0681	0.0677	0.0689	0.0691	0.0686	4340.5
H_δ	–0.0435	–0.0431	...			–0.0432	4102.0
H_ε	–0.1155	–0.1141	...			–0.1153	3970.3
H_ζ	–0.1638	–0.1652	...			–0.1631	3889.2
H_η	–0.1977	–0.1941	–0.1914	–0.1953		–0.1946	3835.5

The next step in this example is to find a connection between the average deviation of a given spectral line from the position of the star's image wihtout any dispering element. In the case of a diffraction grating this is the zeroth order (cf. Part 5, sections 3.2 and 3.3). We may call this the "white" image of the star.

For the determination of a relation between the distance from this "white" image to the position of a line of given wavelength, we choose three lines.

Table 3-3: Three lines chosen for calibration from Table 3-2.

line	$\overline{x}$	λ, Å
H_β	0.2530	4861.6
H_γ	0.0686	4340.5
H_η	–0.1946	3835.5

By using the following equation of dispersion (called Hartmann's in the literature) we may define the scale for all further measurements on a given film or plate by solving for the unknown constants using the calibration lines (ie. data given in Table 3-3):

$$\lambda = \lambda_0 + \frac{c_0}{k_0 - \overline{x}} \tag{1}$$

with λ being the calculated wavelength from the photograph, and c_0, k_0 and λ_0 being constants for the photograph to be derived from the measurement, i.e. we have to find a solution of three equations with three unknowns. $\overline{x}$ is the measured relative position of a spectral line. Therefore, we need at least three spectral lines for the procedure (but more is preferable).
From the values in Table 3-3, the following constants can be calculated: $\lambda_0 = 1665.4$Å, $k_0 = 1.19963$, and $c_0 = 3025.6$. Then we obtain the differences given in Table 3-4. In fact, the differences for the three lines used for calculation should be zero.
With these values we may check the whole measurement done so far:

Table 3-4: Measured and expected wavelengths.

$\overline{x}$, mm	calculated λ	"catalogue" λ_{cat}	difference $\Delta\lambda$, Å
0.2530	4861.6	4861.6	±0.0
0.0686	4340.5	4340.5	±0.0
–0.0432	4099.8	4102.0	+2.2
–0.1153	3966.4	3970.3	+3.9
–0.1631	3885.6	3889.2	+3.6
–0.1946	3835.5	3835.5	±0.0

The differences found are rather small. If you want to derive precise quantities it is necessary to minimize these errors according to the next equation:

$$\Delta\lambda = \Delta\lambda_0 + \frac{\Delta c_0}{k_0 - \overline{x}} - \frac{c_0}{(k_0 - \overline{x})^2}\Delta k_0 \tag{2}$$

This leads us to a system of six equations using the values calculated before:

$$0.0 = \Delta\lambda_0 + 1.06\Delta c_0 - 3399\Delta k_0 \tag{3 – 1}$$

$$0.0 = \Delta\lambda_0 + 0.88\Delta c_0 - 2365\Delta k_0 \tag{3 – 2}$$

$$2.2 = \Delta\lambda_0 + 0.80\Delta c_0 - 1959\Delta k_0 \tag{3 – 3}$$

$$3.9 = \Delta\lambda_0 + 0.76\Delta c_0 - 1750\Delta k_0 \tag{3 – 4}$$

$$3.6 = \Delta\lambda_0 + 0.73\Delta c_0 - 1629\Delta k_0 \tag{3 – 5}$$

$$0.0 = \Delta\lambda_0 + 0.72\Delta c_0 - 1556\Delta k_0 \tag{3 – 6}$$

There are enough equations to solve this whole system. The system of six equation has to be solved by the least squares method (there are only 3 unknowns so a best "fit" has to be made). You may find basics of linear regression in a variety of books. As an example we mention Taylor (1982).
We derive the following, corrected values of the constants for the equation of dispersion using the least-squares method:
$\Delta\lambda_0 = +5.18$
$\Delta\ c_0 = +2.16$
$\Delta\ k_0 = +0.00235$
and, consequently, the dispersion relation to be used is:

$$\lambda = 1680.2\text{Å} + \frac{3002.4\text{Å}}{1.1968 - \overline{x}} \tag{4}$$

Usually, such a corrected equation permits the meteor spectra to be reduced in an accurate way. The amount of measuring error can be expected to be larger than the remaining error included in the formula.

A dispersion relation of the form:

$$\lambda = \lambda_0 + \frac{c_0}{(k_0 - \overline{x})^a} \qquad (5)$$

leads to sufficient accuracy, usually with $a = 1$.

In practice, you may also have a number of "suspected" lines in a meteor spectrum, which then can be used for calibration lines. Then you need to measure only the meteor spectrum and treat the lines as in the above example. You may have to run through the procedure several times.

If only one line is measurable (and this one line must always be the "suspect" line), the constants λ_0 and c can be taken from the calibration spectrum (ie. a star or lamp) and k can be computed from the "suspected" line. In fact, k depends only on the origin of the coordinate system.

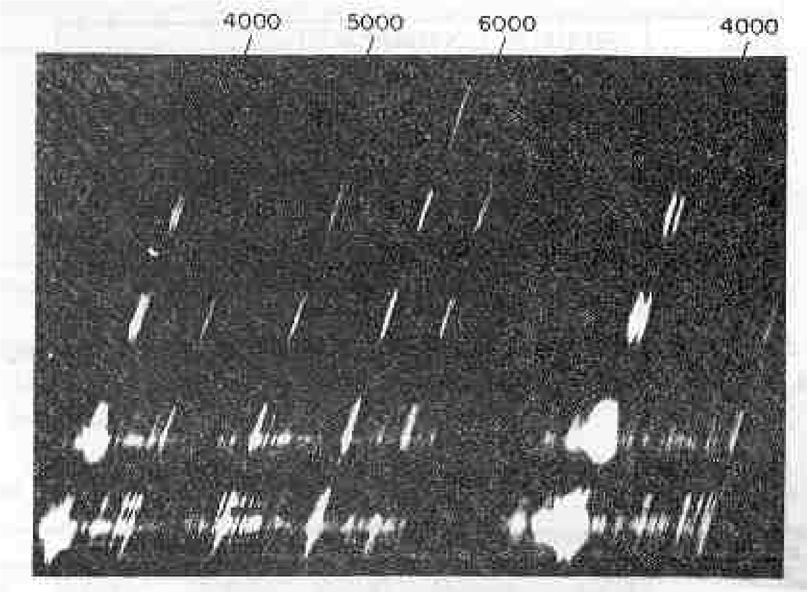

Figure 3-4: Example of a meteor spectrum (from Halliday (1967), p.93).

Knowing the dispersion relation, we now can start measuring the meteor spectrum. Since a meteor spectrum is a line emission spectrum, we are essentially obtaining an image of the meteor in each separate line. The appearance of any given line, its intensity or its disappearance, gives information about the meteoroid, the ablation process as well as the high atmosphere.

We determine the distances between the spectral lines in the direction c (ie. a direction normal to the lines). Furthermore, we need to know the angle ψ between the dispersion direction and the meteor trail, because we have to consider the corrected distances b in the dispersion direction, through the relation

$$b = c \sec \psi = \frac{c}{\cos \psi} \qquad (6).$$

This is for normal dispersion, which allows us to use the relation determined above.

The most intense lines in a meteor spectrum are generally the H and K lines from ionized Calcium (Ca II). These are situated towards the violet end of the spectrum and are quite easy to identify. We may use the coordinates of one of these twin lines as the origin of our coordinate system for measuring the meteor spectrum. Depending on the length of the meteor trail, we will measure the line positions at several points along each line, say near the beginning and the end, and perhaps at flares or other easily identifiable points. This is demonstrated in Fig. 3-5.

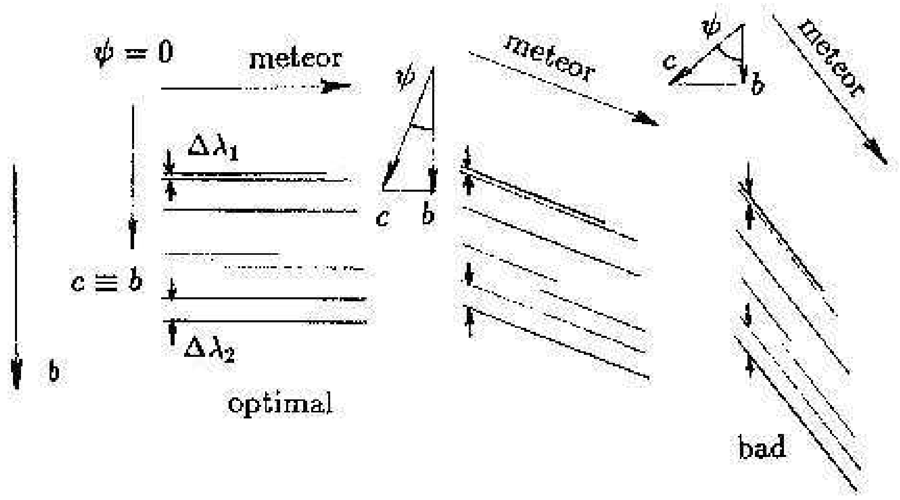

Figure 3-5: Coordinates and angles used for the measurement of a meteor spectrum. The symbols are explained in the text along with the equations and some accompanying instructions.
From this figure it becomes obvious that the angle ψ should be as small as possible. This can be realized, however, only for meteors of a given shower since their directions are known in advance while the directions of sporadic meteors are random. As discussed before, this is achieved by orienting the grating or prism so its long-axis is perpendicular to the expected direction of motion of the meteor. The differences $\Delta\lambda$ otherwise appear to become smaller (smaller Δc, but the same Δb), and small wavelength differences $\Delta\lambda$ become unresolvable as in the case $\Delta\lambda_1$ in the right hand scenario.

We continue to describe the method begun above. The following example is adapted from the Russian Handbook (Bakulin, 1973).
At some chosen n positions, a_n, along the trail (numbered 1 to 5 in our example, Fig. 3-6), we measure the coordinates b_n of the spectral lines. In this example, we choose $l = 8$ lines in order to demonstrate the procedure. The coordinate a is perpendicular to the dispersion direction b, while c follows the meteor's direction.

Table 3-5: Sample of $l = 8$ spectral lines measured as described above. The positions number $n = 1 - 5$ are measured in the direction a, the positions of the lines are then given in b_n [mm] as shown in Fig. 3-6.

position in a [mm]		1	2	3	4	5	line
line number n	$a =$	2.1428	2.1737	2.1967	2.2227	2.2716	intensity
3	$b =$	1.8444	1.8808	1.9108	1.9483	2.0092	–
6		1.9136	1.9496	1.9732	2.0130	2.0730	1
8		1.9665	2.0070	2.0354	2.0680	–	2
9		1.9854	2.0258	2.0540	2.0905	–	10
10		2.0332	2.0742	2.1050	2.1366	2.1959	10
12		2.1167	2.1570	2.1824	2.2157	2.2790	3
15		2.1875	2.2252	2.2540	2.2882	2.3470	1
18		2.2575	2.2922	–	–	–	5

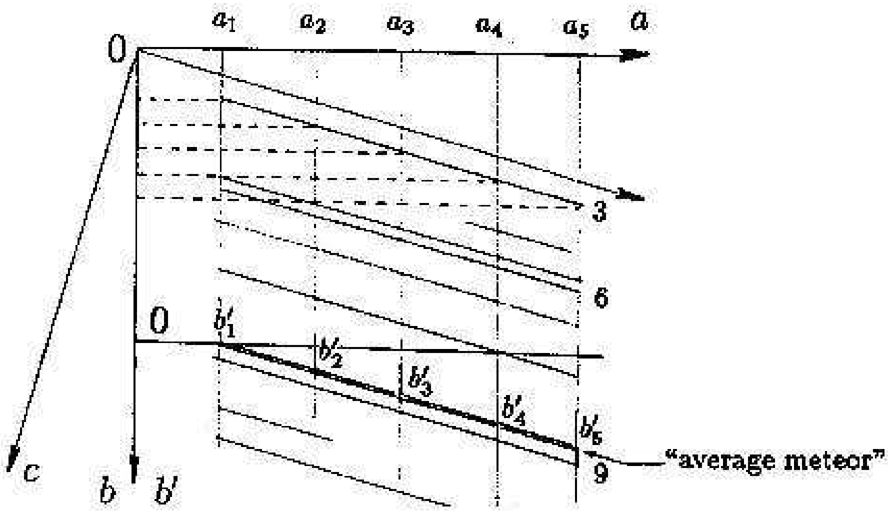

Figure 3-6: Calculation of the "average meteor" from the measured positions of spectral lines.

Next, we choose lines that were measured at all positions along the trail. In our example, these are the lines 3, 6, 10, 12 and 15. Their coordinates b_n are averaged now, i.e. we calculate the "average meteor". For example, the point $n = 1$ with the coordinate a_1 given in the table above, was measured at

$b_{3,1} = 1.8444$ (line 3, position 1),
$b_{6,1} = 1.9186$ (line 6, position 1),
$b_{10,1} = 2.0332$ (line 10, position 1),
$b_{12,1} = 2.1167$ (line 12, position 1) and
$b_{15,1} = 2.1875$ (line 15, position 1).
The average position is $\overline{b_1} = 2.0191$.
This point we define as the beginning of the coordinate parallel to a, and set it to $b'_1 = 0$.
The other average coordinates b_n are $\overline{b_2} = 2.0574, \overline{b_3} = 2.0854, \overline{b_4} = 2.1204$ and $\overline{b_5} = 2.1808$.
Since $b'_1 = 0$, we find $b'_2 = \overline{b_2} - \overline{b_1} = 0.0383$,
and furthermore $b'_3 = 0.0663, b'_4 = 0.1013$ and $b'_5 = 0.1617$.
As shown in Fig. 3-6, we now have defined the "average meteor" and have shifted the coordinate b and may also find the average positions of the spectral lines in the b' coordinate system.
With these figures we may reduce the values determined in Table 3-5 to average positions, as shown in Table 3-6. We also "suspect" lines 8 and 9 to be the Calcium Ca II doublet, with line number 8 = Ca K with $\lambda = 3934$Å. With the help of the dispersion relation, we now may identify the other lines. We put this value for line number 8 into the equation

$$\lambda - 1680.2 = \frac{3002.4}{1.1968 - \overline{x}} \tag*{(7),}$$

i.e.

$$3934 - 1680.2 = \frac{3002.4}{1.1968 - \overline{x}} \tag{8}$$

and find $\overline{x} = -0.1351$. From our measurements we obtained the coordinate $\overline{b_8} = 1.9678$, and we now need to know the values of $\overline{x}$ for the other lines n as well as to calculate their wavelengths from the dispersion relation. For each line n we now may find

$$\overline{x_n} = \overline{b_n} - \text{const} \tag*{(9).}$$

From the first case we calculate const $= \overline{b_3} - \overline{x_3} = 1.9678 + 0.1351 = 2.1029$ for the identified line 8. Now we find the other $\overline{x_n}$, and consequently also their wavelengths.

Table 3-6: Final calculations after line number 8 assumed to be Ca K (3934 Å).

line number	1	2	3	4	5	$\overline{b_n}$	$\overline{x_n}$	λ
3	1.8444	1.8425	1.8445	1.8470	1.8475	1.8452	−0.2577	3744
6	1.9136	1.9113	1.9119	1.9117	1.9113	1.9120	−0.1909	3844
8	1.9665	1.9687	1.9691	1.9667	–	1.9678	−0.1351	3934
9	1.9854	1.9875	1.9877	1.9892	–	1.9874	−0.1155	3968
10	2.0332	2.0359	2.0352	2.0353	2.0342	2.0348	−0.0681	4054
12	2.1167	2.1187	2.1161	2.1144	2.1173	2.1166	+0.0137	4218
15	2.1875	2.1869	2.1877	2.1869	2.1853	2.1869	+0.0840	4378
18	2.2575	2.2539	–	–	–	2.2557	+0.1528	4556

We now present a table of selected lines which were found in meteor spectra (Tab. 3-7). A longer list is given by Ceplecha (1966) and Ceplecha (1971).

Table 3-7: List of spectral lines frequently found in meteor spectra and their relative intensities. The identification of the lines (numbers) in our example is also given. Lines marked with an asterisk appear bright in spectra of fast meteors, such as the Perseids, but much fainter in spectra of slow meteors.

Laboratory data			ident.	Laboratory data			ident.
λ_{lab}, [$\mathring{A}$]	atom/ion	intensity	number	λ_{lab}, [$\mathring{A}$]	atom/ion	intensity	number
3719.9	Fe	10	2	4923.9	Fe$^+$	2*	
3734.9	Fe	8		4957.6	Fe	4	
3737.1	Fe	9	3	5012.1	Fe	1	
3745.6	Fe	8		5018.4	Fe$^+$	3*	
3749.5	Fe	8		5110.4	Fe	1	
3820.4	Fe	9		5167.3	Mg	17	
3825.9	Fe	8		5172.7	Mg	25	
3829.4	Mg	10		5183.6	Mg	28	
3832.3	Mg	11		5208.4	Cr	10	
3838.3	Mg	12		5227.2	Fe	5	
3859.9	Fe	11		5269.5	Fe	14	
3886.3	Fe	9		5328.0	Fe	12	
3933.7	Ca$^+$	40*	8	5371.5	Fe	9	
3968.5	Ca$^+$	35*	9	5397.1	Fe	5	
4030.8	Mn	10		5405.8	Fe	6	
4045.8	Fe	10		5429.7	Fe	6	
4063.6	Fe	9		5434.5	Fe	4	
4131.0	Si$^+$	1*		5446.9	Fe	4	
4226.7	Ca	11	12	5455.6	Fe	4	
4254.4	Cr	9		5528.4	Mg	2	
4271.8	Fe	10		5615.7	Fe	1	
4274.8	Cr	8		5890.0	Na	40	
4289.7	Cr	7		5895.9	Na	35	
4307.9	Fe	10		6156.8	O	1*	
4325.8	Fe	10		6162.2	Ca	1	
4383.5	Fe	14	15	6347.1	Si$^+$	6*	
4404.8	Fe	11		6371.4	Si$^+$	3*	
4481.2	Mg$^+$	15*		6495.0	Fe	1	
4920.5	Fe	3		6562.9	H	2*	

Another way to relate measured coordinates x of dispersion into wavelengths λ is through the use of an interpolation polynomial, especially for gratings. (A simple linear dispersion is a good first approximation for grating spectra.) You should have several lines already identified (or with "suspected" identifications) and make a fit using a polynomial of degree somewhat less than the number of identified lines. You can check your preliminary identifications of lines and add more identifications by the fit obtained with this polynomial. You can use this procedure iteratively, up to a degree of about 6 to 8. Then you can use the final polynomial to try to identify all spectral lines in your meteor spectrum (Ceplecha, 1991).

A meteor spectrum photographed with an *optical transmission grating* is usually off the optical axis of the camera. The diffracted rays of different wavelengths lie on the surface of a cone, the axis of which is parallel to the grating grooves. The section of the diffraction cone intersected by the focal plane is the diffraction hyperbola, along which the spectral record is distributed. Absolute wavelengths can be found from such a spectrum if it includes the zero-order image.

An excellent example of a fireball spectrum was provided by Jiři Borovička. It is reproduced and explained in detail in the photograph section in Part 10 of theis Handbook.

A method for wavelength determination from spectra obtained through diffraction gratings is described by Ceplecha (1961). The spectrum must be photographed with a rotating shutter. The measurements of one break in three different lines then define the diffraction hyperbola, and thus the connection between the coordinate system of the plate and that of the grating. The coordinate system of the grating directly determines the position of individual lines, so if we know the precise number of grooves per millimeter and the direction cosines of the zero-order image of the meteor, wavelengths of all lines can be computed without previous identification (Ceplecha, 1961; Ceplecha and Rajchl, 1963).

Finally, we note that a list of 189 line identifications in a meteor spectrum can be found in Ceplecha (1966) and a list of 990 lines identified in a fireball spectrum is given by Ceplecha (1971).

The photometric calibration of a spectrum is of interest if line intensities should be determined. However, this is a very specialized task and is not further described here. The basic procedure involves finding the characteristic curve of the film as described in Part 8 (Photometric measurements). This can be done from zeroth order star images for grating spectra. To permit the comparison of line intensities, the correction for the sensitivity of the film to different wavelengths must be applied. The spectral sensitivity curve of a given emulsion can normally be obtained from the manufacturer or may be measured on a known spectrum.

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