



Catch a star 2005:



The magic of dancing spectral lines in the spectrum of *Beta Aurigae*

by Helena Fischer, Malte Baer, Jerome Wolpers and Martin Falk (teacher)

1. **Abstract: Who's who and what are we up to?**
2. **A portrait of our star and some theory from ancient history to modern astrophysics**
 - 2.1 **Mythological background of Auriga (The Charioteer)**
 - 2.2 **Beta Aurigae (Menkalinan – Arabic name for “the shoulder of the charioteer”)**
 - 2.3 **Theoretical aspects of star spectra**
 - 2.4 **Further astrophysical data accessible by school-astronomy and intermediate results of our astronomy group**
3. **Our equipment for spectrum analysis**
 - 3.1 **The telescope**
 - 3.2 **The camera and photographic techniques**
4. **The Professional Spectrometer (Bausch & Lomb) of 1960s**
5. **The final countdown**

1. Abstract: Who's who and what are we up to?

We – the star-catchers of 2005 – have been members of an astronomy group [1] of two local highschools for a few years. Our place of observation is situated some 20 miles south of Hamburg in Northern Germany under a dark sky, but often under many clouds. When the good news of “catch a star 05” was received, we made up our minds about a running project in our astro-group, which is related to analysing starlight by spectroscopy with the instruments of hobby-astronomers. Last winter we were eye-witnesses of the work of some astro-friends of ours, who spent lots of winter nights in catching “high resolution” spectra, not only of bright stars – but of so-called “spectroscopic binaries”.

Unfortunately, what looks like “high” in school astronomy is relatively “low” in scientific astronomy. Nevertheless we decided to top the results of our friends by modifying some techniques and to test them on the only bright and fast rotating “spectroscopic binary star” we know of: **Menkalinan** – close to Capella and easy to observe in clear winter nights – scientifically called “**beta Aurigae**”. Our aim: We wanted to detect and measure the shift of spectral lines in the course of revolution of this star system. Here is our report of “advanced spectroscopy” with good luck in technology and bad luck in meteorology.

[1] further details on our homepage: <http://www.gemini-astronomie.de/>

2. A portrait of our star and some theory from ancient history to modern astrophysics

2.1 Mythological background of Auriga (The Charioteer) [2]

Originally this constellation had been called "goat with the kid". Later it was renamed "Auriga". On old star maps the Charioteer carries a goat on his back and some goat kids in his hand, too. The goat is supposed to show Amaltheia, famous for suckling Zeus as an infant who had to hide from his father Kronos. Previously Capella, the brightest star of this constellation, was called Amathelia. After taking over the reign of the olymp, Zeus put the goat at the sky to show his gratitude.

The name Auriga (The Charioteer) is explained in different ways: Another possible explanation is that the constellation represents Erichthonius, a snake-footed king and son of Hephaestus and Mother Earth, who invented the chariot pulled by four horses so that he could get around faster. This impressed Zeus so much that he placed the man and his chariot in the heavens.

[2] <http://www.heavens-above.com/myth.asp?con=Aur>

2.2 Beta Aurigae (Menkalinan – Arabic name for "the shoulder of the charioteer")

Beta Aurigae is the third brightest star in Auriga ("beta" Aurigae is less bright than Elnath on the border of the constellation Taurus). Actually *beta Aurigae* is a set of two stars revolving each other in a period of 3,96 days [3]. Beta Aurigae is a "spectroscopic" binary system consisting of two almost identical subgiant A stars. Both are about 48 times more luminous than the Sun and their distance is only about one-fifth of the distance between Sun and Mercury. Thus they distort each other into an ellipsoidal shape by tidal forces (cf.Ch.[5]).

These are the normal catalogue details [4] of *beta Aurigae* and how it looks like through a normal telescope (we mounted a digital camera on top of the eyepiece for a 15 sec exposure). More specified data as well as Aladin-digitized photographs are in reach by CDS-online [5].

Visual Magnitude 1.90

Absolute Magnitude -0.11

Spectral type A2V



Surface temperature 9.200K

Luminosity 95 L_{sun}

Distance 82 light-years

Position R.A. 05h 59m 32s, Dec: +44° 56' 51''

Every telescope positioned on *beta Aur* shows **one** bright bluish star (among other stars of $\sim 10^{\text{th}}$ magnitude) and further details of the star can only be detected by analysing the starlight when it is split up into the “rainbow colours” by means of a prism – or better by a grating, resulting in a typical star spectrum.

[3] first discovered and analysed in 1889 by Antonia Maury

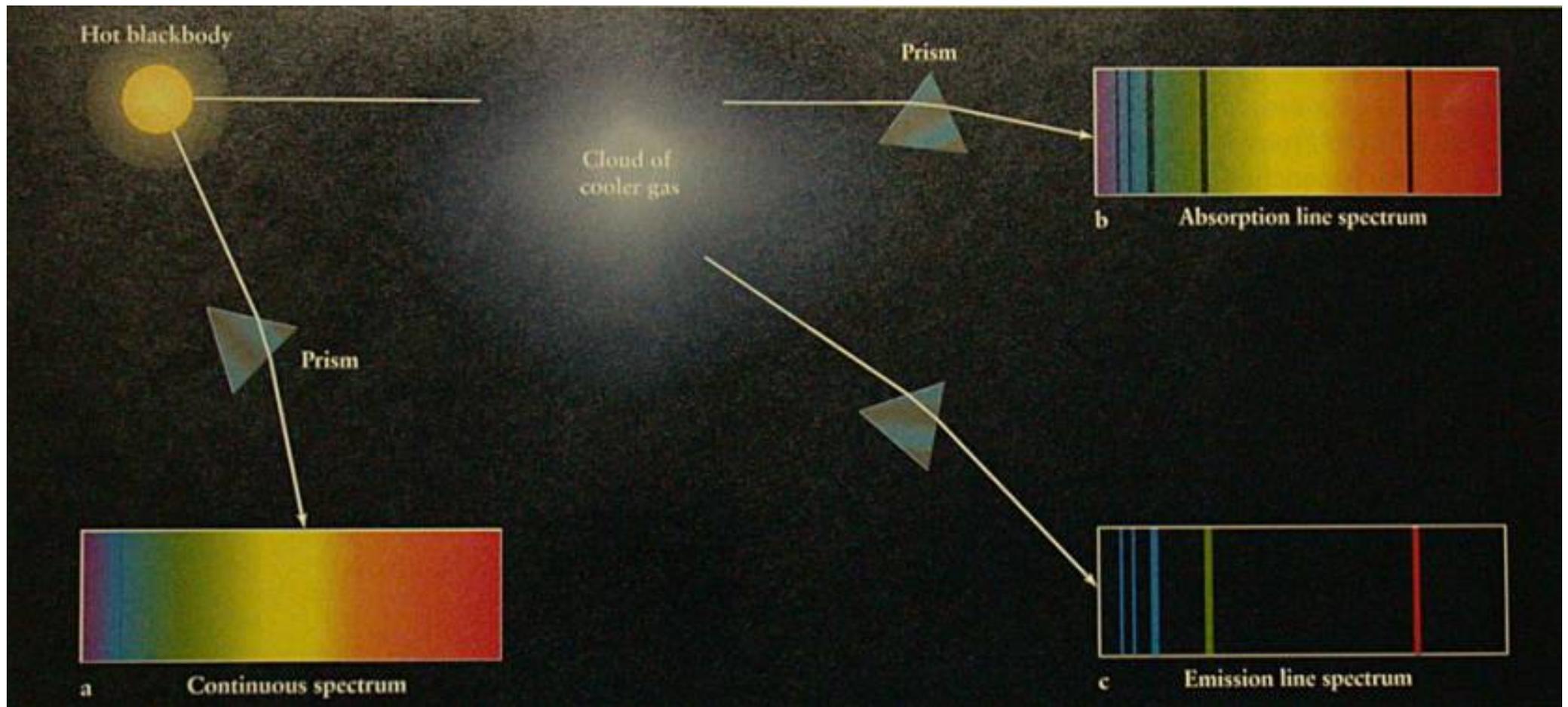
[4] <http://www.daviddarling.info/encyclopedia/M/Menkalinan.html>

[5] <http://vizier-u.strasbg.fr/viz-bin/>

2.3 Theoretical aspects of star spectra [6]

Star spectra emerge when a diffraction grating is used in the (parallel) beam of starlight gathered by a telescope, splitting the white “mixture” of light-particles/waves. By passing the grating – either a reflecting type or a transmission grating – the many tiny slits representing the grating diffract almost each particle/wave into a sequel of coloured photons separated according to their wavelengths: red light (photons of lesser energy and longer wavelength) are refracted less than the blue ones (photons of higher energy and shorter wavelength). The resulting image of the original white light is the well known set of “rainbow colours”. The more professional a spectrograph does the diffraction by means of a high-quality grating (the “heart of the spectrograph”) the more details of the source of light is shown in the spectrum.

In order to outline our understanding of the origin of these details we concentrate on major phenomena in stellar spectra as represented in this illustration [7]:



As a star radiates light from the scientifically called **"hot black body"** (resulting in a **continuous spectrum**), its temperature, pressure and gaseous elements in its atmosphere modify the "layout" of its spectrum resulting in **absorption lines** overlaying the continuum. Sometimes even **emission lines** occur, depending on the conditions of stellar atmospheres. Further information is received, when spectra are interpreted by applying spectral analysis in modelling theories of stellar development. Though all stellar spectra seem to be unique, they form classes according to characteristic aspects of temperature and lifetime. This is subject to the interpretation of the *Hertzprung-Russel-diagram* of stars. Our interest is focused on a special tool in astronomy: even the star's velocity relative to our line of sight can be determined by observing, whether the (absorption)lines move towards the blue or red end of the spectrum. This shift of spectral lines is of great importance in astronomy, especially in measuring distances (the redshift) of galaxies – but out of reach to amateur astronomy, due to a costly high-resolution spectrograph with a proper grating and additional optics. Every good educational means in astronomy demonstrates this traditionally important tool in understanding stellar motion.

Thus the term **spectroscopic binary** star-system refers to double (or more)-stars which reveal their double existence only by

interpreting the tiny shift of absorption lines on the base of the **Doppler effect** of wavelengths of light:

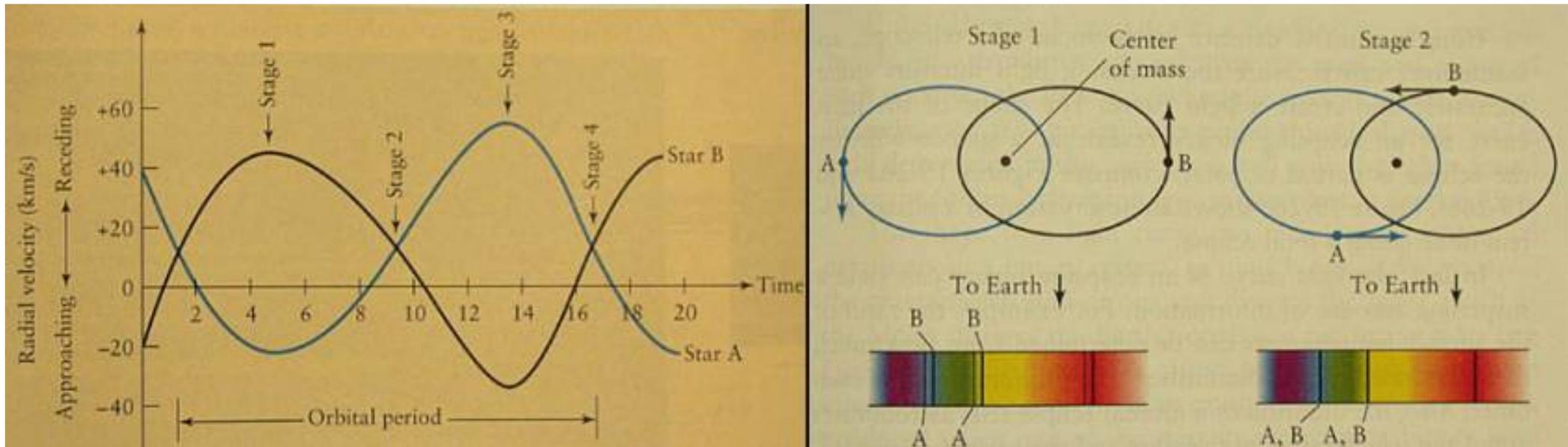
Example: The wavelength of the Ca II emission line in a laboratory is $\lambda_0 = 448.1 \text{ nm}$. In case we determine the same line as absorption line in the spectrum of beta Aurigae at $\lambda = 447.9 \text{ nm}$, the resulting radial velocity can be computed according to Doppler's formulas:

$$\Delta\lambda = \lambda - \lambda_0 = 447.9 - 448.1 = -0.2 \text{ nm}$$

(beta Aur is approaching - $\Delta\lambda$ is negative, i.e. blue-shifted - relatively to our line of sight while sending out the proper (lack of) photons.

In order to compute the radial velocity of the star we apply $v = c \cdot \Delta\lambda / \lambda_0 = 300\,000 \text{ km/s} \cdot -0.2 / 448.1 = -133.89 \text{ km/s}$
(The example uses rounded measured data [8] but neglects the relative motion of the earth)

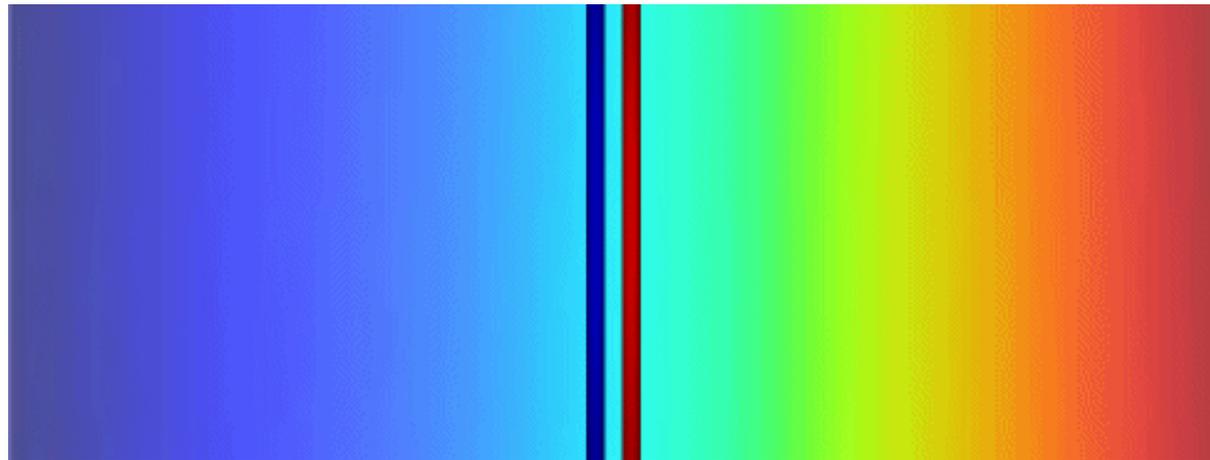
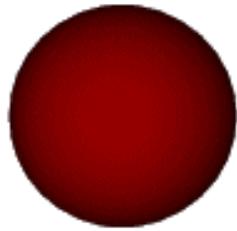
To understand the graphic display of radial velocities of a typical binary star system,



ill: cf ref [7]

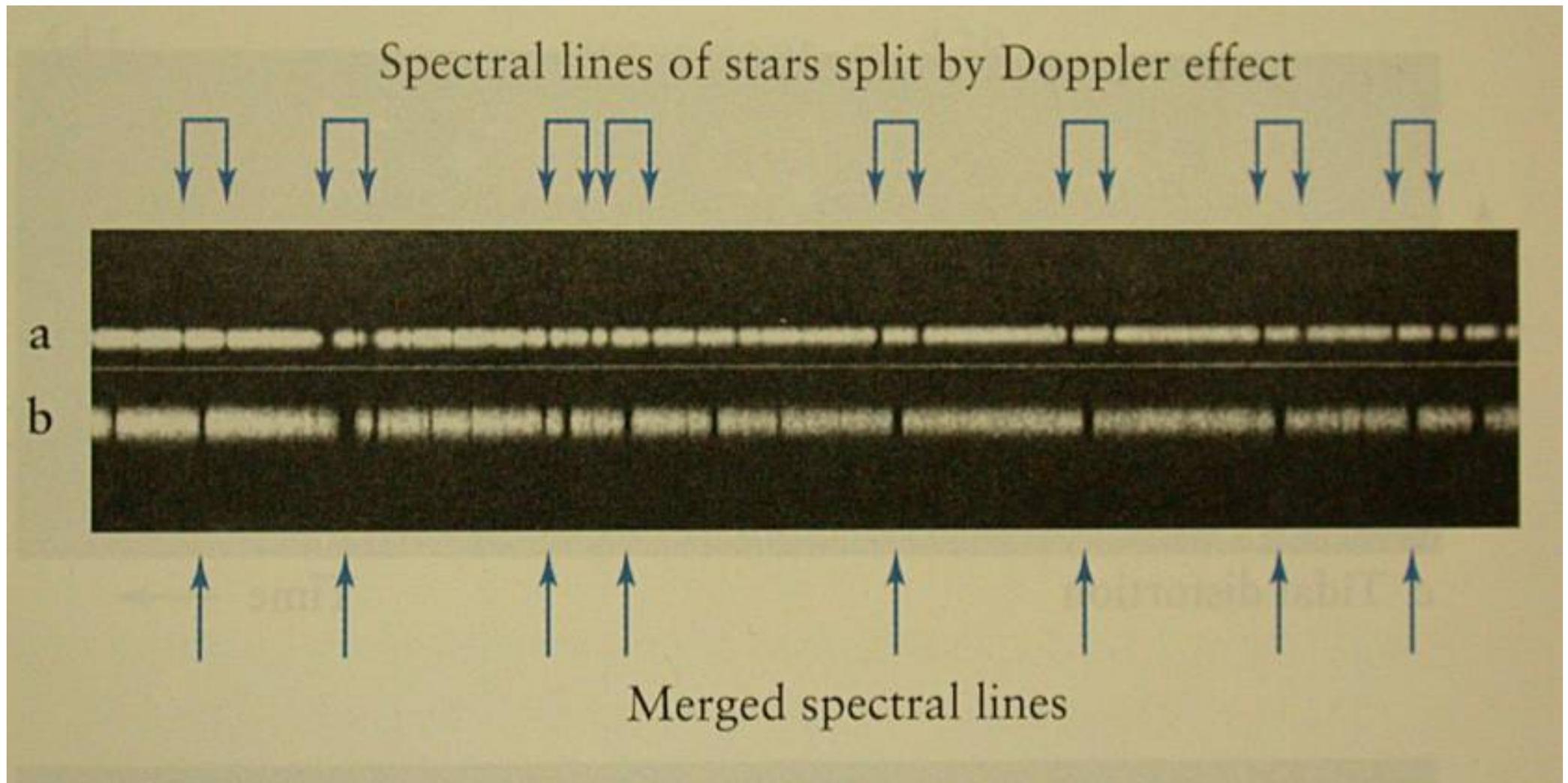
where the measured velocity is plotted against the time, we arranged a simulation showing the effect of the "dancing" spectral lines. A detailed simulation of various stellar parameter is presented in the internet [9]. We have concentrated on major effects, possibly detectable with our equipment.

Model:



ill: (check for simultaneous download in order to synchronise both animations)

Unfortunately, the measurable effects regarding spectral lines depend on high quality equipment, normally exceeding amateur observational means, which is sometimes footnoted under images like this one showing the effect of blue-vs-red split lines.



ill: cf ref [7]

Nevertheless, a closer look and analysis of results of our astronomy workgroup is worth mentioning.

[6] cf: van Zyl, J.E.: Unveiling the universe; London 1996 pp. 39 ff

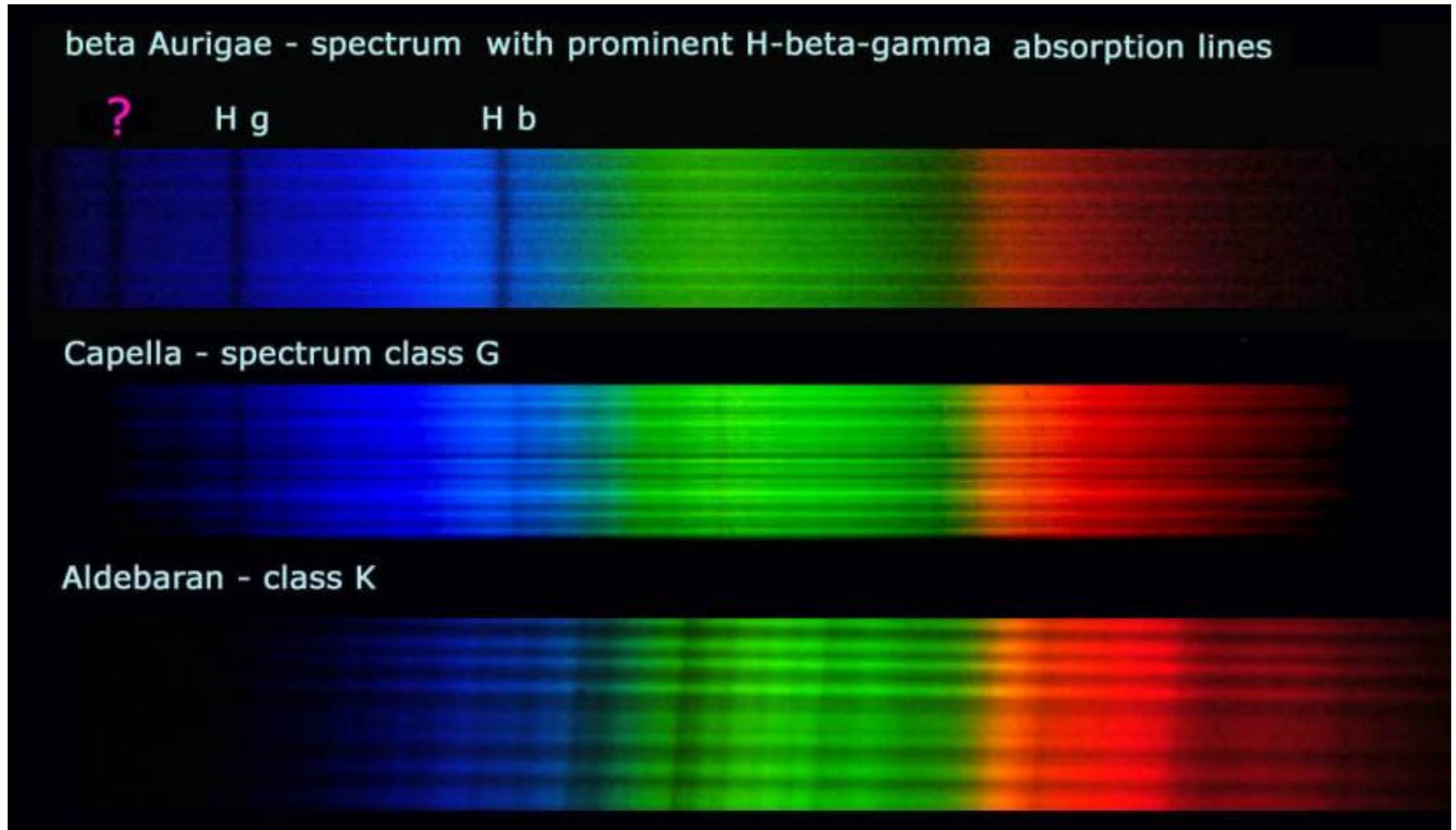
[7] Freedman, R. et al: Universe; New York 2002 pp 107ff

[8] Struve, Otto et al. 1953 PASP 65 via internet

[9] <http://astro.ph.unimelb.edu/>

2.4 Further astrophysical data accessible by school-astronomy and intermediate results of our astronomy group

In amateur astronomy the only (affordable) standard spectroscope is a transmission grating with ~ 200 diffracting lines/mm mounted in front of the eyepiece –or camera- of the telescope. Due to a blaze-angle of the carrier-glassplate (the effect is that of a prisma of ~ 5 degrees) more light is directed to the 1. (blazed) order of the spectrum. The resulting images offer deeper insights into stellar parameter as a further step to “high resolution” spectroscopy. (The technical procedure of spectrography will be explained in chapter 3.) We refer again to an astronomy textbook [10] to explain the main aspects of spectra.



sections of 20 sec exposures of the blazed 1.order of 200 lines/mm transmission grating, placed ~ 15 cm in front of the CCD (Nikon DSLR)

3.3.04 - 22:00 - 23:00 by gemini-astro

The illustration is our Photoshop composite of spectra from the mentioned stars showing some typical parameters of stars and their spectral classes: (the O-B-A-F-G-K-M-L-T sequence is the latest edition)

In the spectrum of a star like *beta Aur* (Class A) three to four spectral lines can be detected, at least two of them represent the Balmer lines of hydrogen. These absorption lines occur in spectra of high temperature stars (~11000 to 7500 K), when the electron of a hydrogen atom encounter a transition from a higher level to level 2, emitting – or absorbing a photon (cf ill.). The appropriate wavelength of these transitions – photons in the visible range of spectra was first discovered by J.J. Balmer in 1885 and identified as $H\beta = 486.132 \text{ nm}$.

The ?-marked line in *beta Aur* is either the $H\gamma$ -line or, according to a catalogue of spectral classes - or the above mentioned Ca I line. The resolution of our transmission grating and the projection of the spectrum on the CCD-focal plane cannot resolve further details. Nevertheless, further aspects can be discussed in the following spectra of Capella and Aldebaran.

Lower temperatures in the atmosphere of a Class G-star like Capella, having roughly the temperature of our sun, reveal more spectral lines of various elements and have their maximum energy according to the Black-body-radiation curve in the green section of the spectrum as it appears a bit brighter in the image.

A relatively cool star like Aldebaran, representing Class K with stars of ~3500 K, appears to be redder than G-stars and has more (heavier) elements.

Our spectra – photographed in March 04 by our astro-friends – show aspects of the above mentioned theory of stellar evolution and even wavelengths can roughly be determined according to their graphic display in relation to a reference line.

We have attempted to refine some photographic techniques in order get closer to a higher resolution, which is described in the following chapter.

[10] cf: van Zyl, J.E.: p 42

3. Our equipment for spectrum analysis

3.1 The telescope

When relatively dim starlight, even of bright stars in comparison to light of the sun, is to be analysed the need of a powerful

telescope is obvious, which gathers as many photons as possible. Our "scope" has the following technical data: **reflector-type: Maksutov-Cassegrain; aperture: 250 mm; focal length: 3325mm** (reducible by means of a lens 0.6x); on a heavy mount (German Equatorial) and motor-driven in both axis. It has to be positioned manually by means of setting circles or visually before the motors take over control.

3.2 The camera (as a low-resolution spectrograph)(cf.2.4) and photographic techniques [11]

For maximum resolution in spectroscopy we make use of a digital SLR-camera (Nikon D100), which is regularly fitted to the telescope by a T2-adapter. By applying the transmission grating the problems arise:

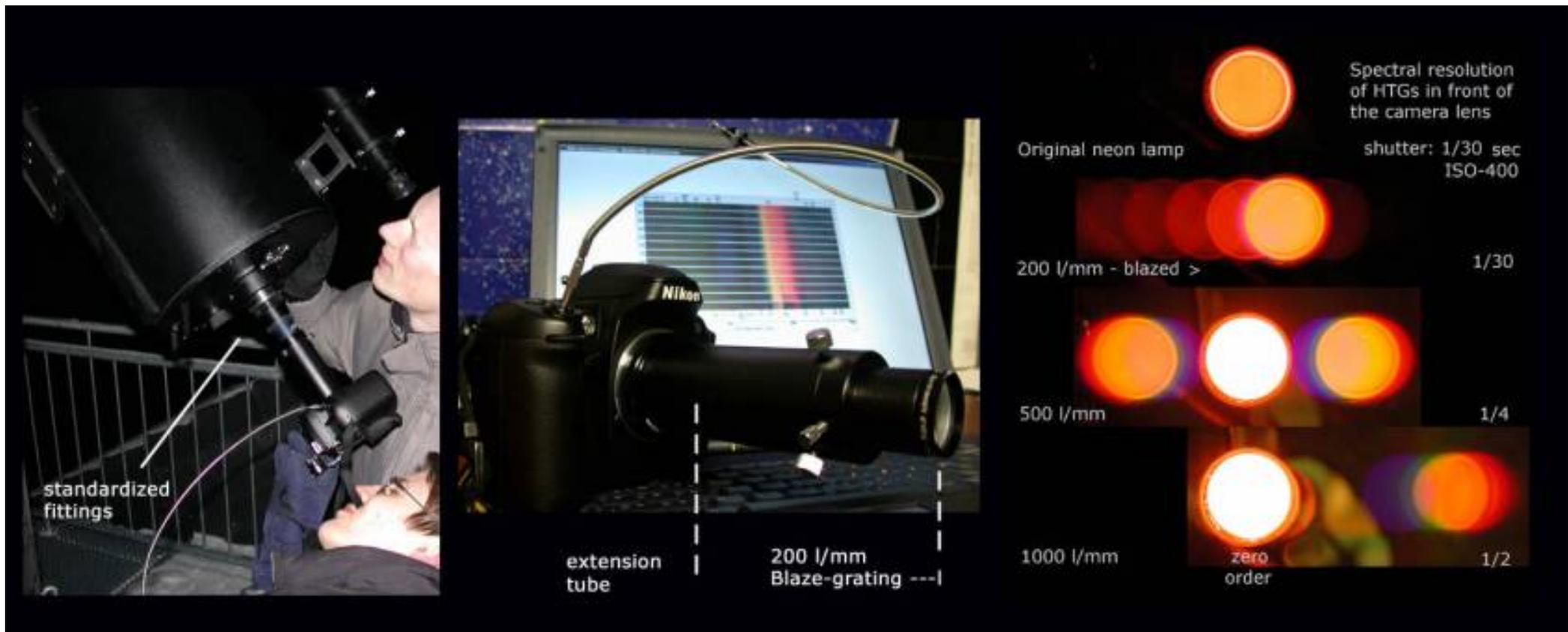
- a. it has to be positioned as far as possible (~15 cm with a DSLR in relation to the size of the CCD) in front of the focal plane of the telescope-camera system to obtain a widespread continuous spectrum (-bright stars allow a visual control in the viewfinder)
- b. to avoid distortions, the spectrum, that looks like a coloured fathom in the viewfinder, has to be aligned to the longer side of the CCD/viewfinder near to the center; focus control can be checked with the help of the 0th order, where the star still looks like a star
- c. during exposure of bright stars the motor will be switched off and after ~20 sec (ISO setting ~400+) a spectrum as shown above appears and can be processed (in Photoshop) (less bright stars need some more experiments with the tracking motor in R.A. direction)

As mentioned above, we tried to modify the resolution by applying a **holographic transmission grating**, which is a cheap educational means sold by optical instrument companies [12]. Two types of gratings are offered, framed in a 5 cm paper-slide-frame: 500 lines/mm for observing the set (first two orders) of spectra, and 1000 lines/mm showing more details. The 500-type can easily be adapted inside the T2-camera adapter and fixed with tape:

The grating is then placed 5 cm in front of the CCD/film plane and, according to its angular diffraction of different wavelengths, a spectrum of higher resolution is obtained in the above described manner.

This does not function with the 1000-type, because the angle of diffraction is too wide to be placed on the CCD. (Some other "tricks" with low-cost gratings are possible) [13].

The set of instruments are shown here:



As one can see in the resolution image does the 500-type of grating produce a fairly better spectrum on the cost of a much longer exposure, because starlight is split into no blazed order, but spread into many of them. When we tried to apply this to *beta Aur* in the hope of a higher resolution good luck struck.

[11] the telescope store provides the grating and a manual
cf: www.baader-planetarium.de

[12] cf: www.edmundoptics.de

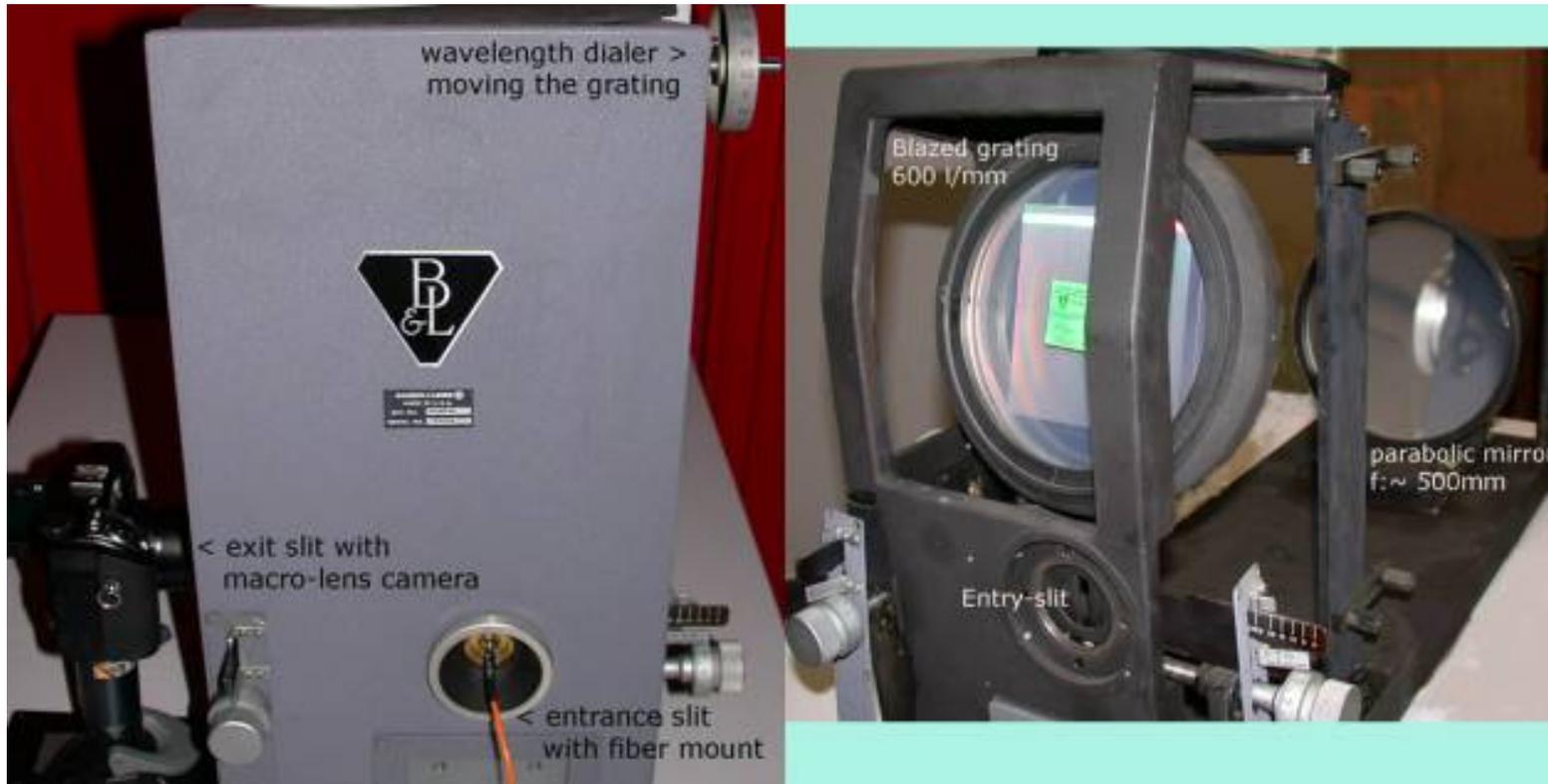
[13] will be published later on our homepage

4. The Professional Spectrometer (Bausch & Lomb) of 1960s

Since measurements of the spectroscopic shifting of absorption lines belong to the field of professional astronomy with its highly specialized equipment, we were restricted to a rough impression of possible effects in the way we have described above.

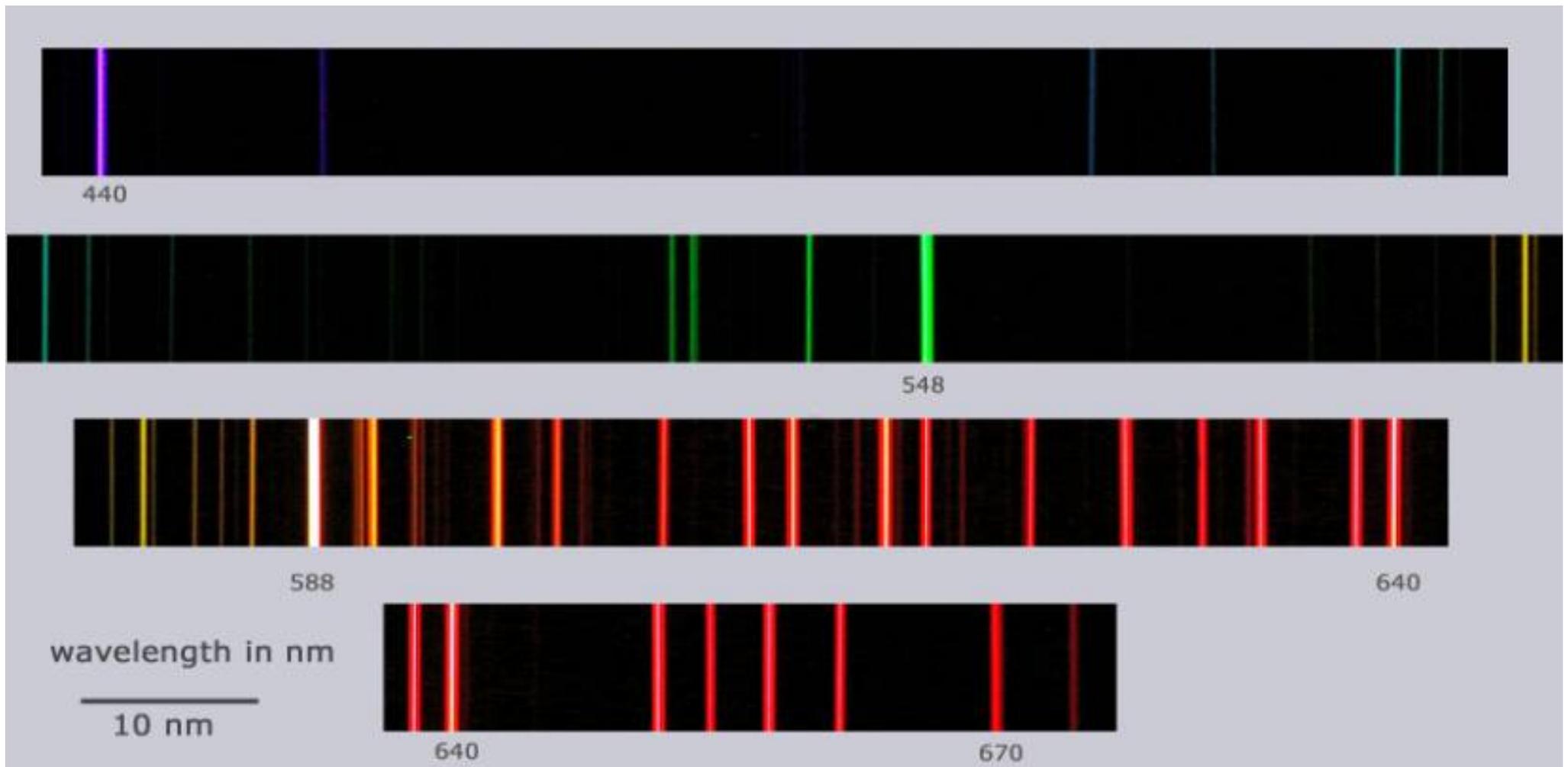
But one day in autumn of 2004 the situation changed dramatically:

A professor of the Technical University Hamburg-Harburg, who knew about our astronomical activities, offered us a "retired" spectrometer of the 60s out of the catacombs of the department of physics for didactical purposes.



ill: front view and inner components of the Bausch & Lomb spectrometer

Soon after some restorations of screws, scales and structural components we found out its impressive resolution by means of the above mentioned neon lamp and its many emission lines.

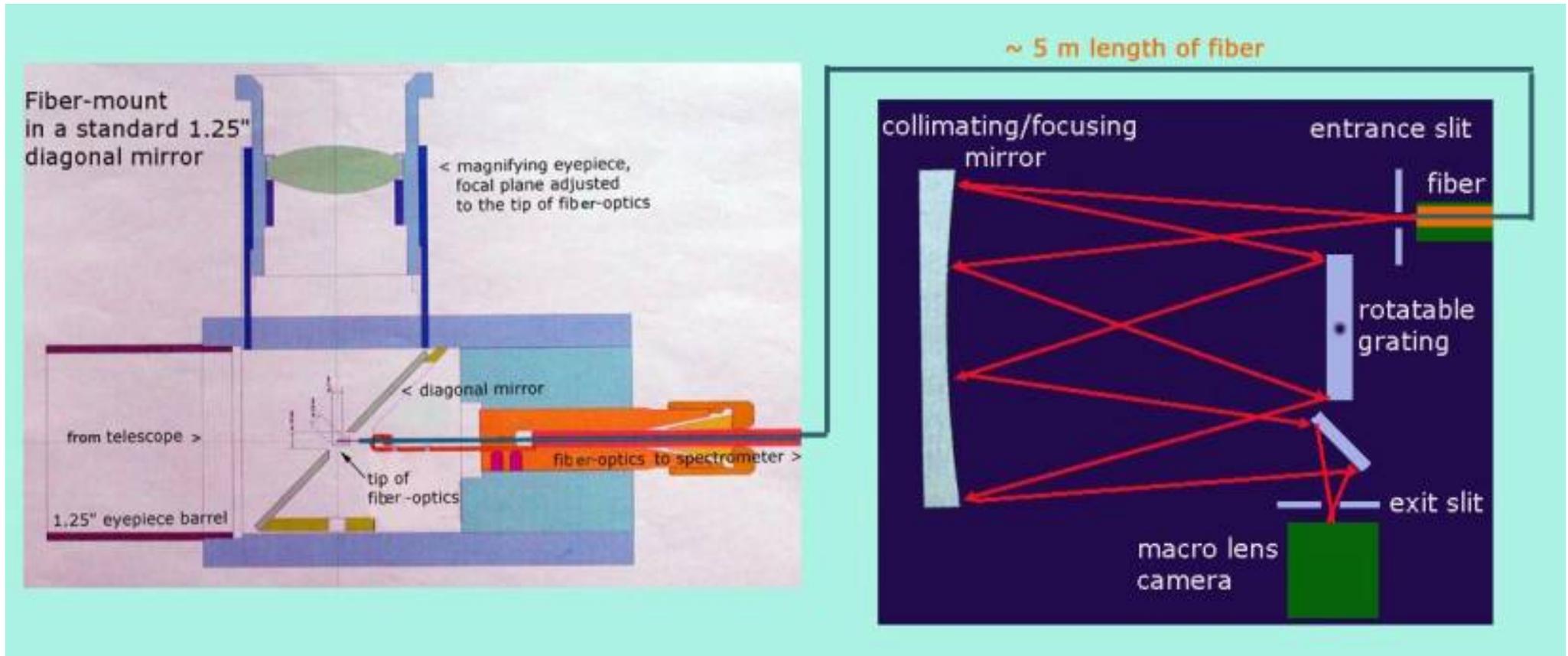


ill: a Photoshop-composite of about 15 macro-lens photographs from the exit-slit of the spectrograph, visually determined/calibrated by dialing the wavelength to the center of a narrow exit slit.

The resulting resolution [14] of the **spectrometer (blazed grating of 600 lines/mm and a parabolic mirror of 500 mm focal length)** in cooperation with the macro-camera system was estimated to be 0.05 nm/pixel; well above everything we have ever measured in spectroscopy.

Consequently the light of *beta Aurigae* could have been spectroscopically analysed, if it were led somehow to the 25kg spectrometer. This should have been no problem by means of fibre-optics – but all amateur astronomers who have experimented with fiber-optics expressed their extreme difficulties in placing and holding the Airy-disc of the star focused by the telescope onto the tip of the fiber (cf. [15]). We designed the gadget below and fortunately found an experienced optician who built the instrument [16] – our professor himself.

The complete set of advanced spectroscopy:



ill: a sketch of the components and the plotted starlight path to the camera

After many hours of training, testing and improvements we finally were awaiting at least two nights of clear sky around Christmas 04, but the heavens remained closed.

Meanwhile some convictions in our achievements, especially in our ability to hold the star on the tip of the fiber for several minutes during the exposure, rested in a test photo of the CaII absorption line (see below), but it was the one of *Sirius*, the brightest available star in winter nights – about 3.5 mag brighter than *beta Aurigae*.

[14] a closer inspection of the linear dispersion results in
 $D = dx/d\lambda = 0.30 \text{ nm/mm}$ in the focal plane of the exit slit

[15] <http://www.astronomie.de/spektrography>

[16] construction details will soon be published on our homepage

5. The final countdown

Spectroscopic binaries, together with eclipsing binaries, are closely monitored in astronomy, so we had to find out further information about the phase and light-curve of the system. Fortunately the University of Krakow, Poland [17] offers a calculator of minima in eclipsing based on latest reported observations. For our task it meant that the maximum expectable separation of spectral lines (due to its perfect inclination of ~ 0 degrees to the line of sight and its 3.96 days period) occurred every second night around Christmas 04 in the early morning hours, where *beta Aurigae* is passing the light dome of Hamburg. Better days will come in the end of January when *beta Aur* is passing the zenith at the phase of widest separation so that we possibly could detect the line shift throughout a longer phase of the period.

Finally the deadline of Catch a star 05 has won the race against nature and especially the weather, since we have no image of *beta Aurigae* Ca II line.

What we have got is the document of **Otto Struve's et al. historical measurement** of the "dancing" lines (cf: ref [8]): probably measured with the same type of spectrometer (but with one of the largest telescopes of that time under a perfect Californian sky) in 1953:

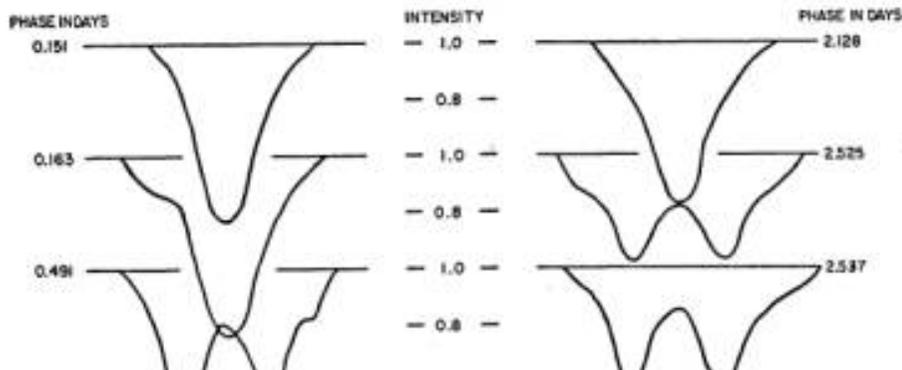
THE SPECTRUM OF BETA AURIGAE (Abstract)

OTTO STRUVE AND CLARE DRISCOLL

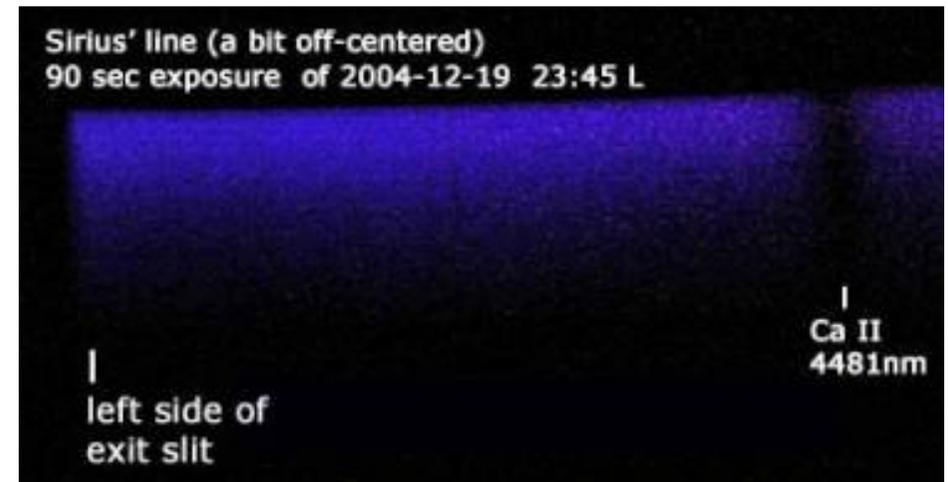
Berkeley Astronomical Department, University of California

Figures 1 and 2 show the profiles of the lines *Ca II K* and *Mg II 4481* on twelve Mount Wilson coude spectrograms (dispersion 3 Å/mm). In each profile the red component is plotted on the left-hand side. The phases were computed with the formula used by B. Smith.¹ At phase zero the less massive component is eclipsed.

As was already shown by R. M. Petrie, the more massive



And this is our **Photoshop simulation** on the base of our photography of Sirius' Ca II line:



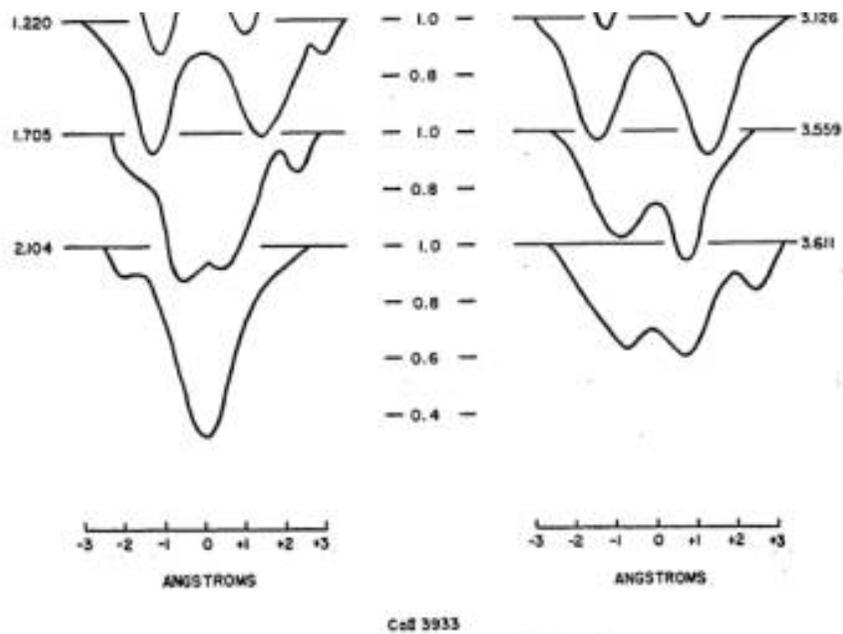
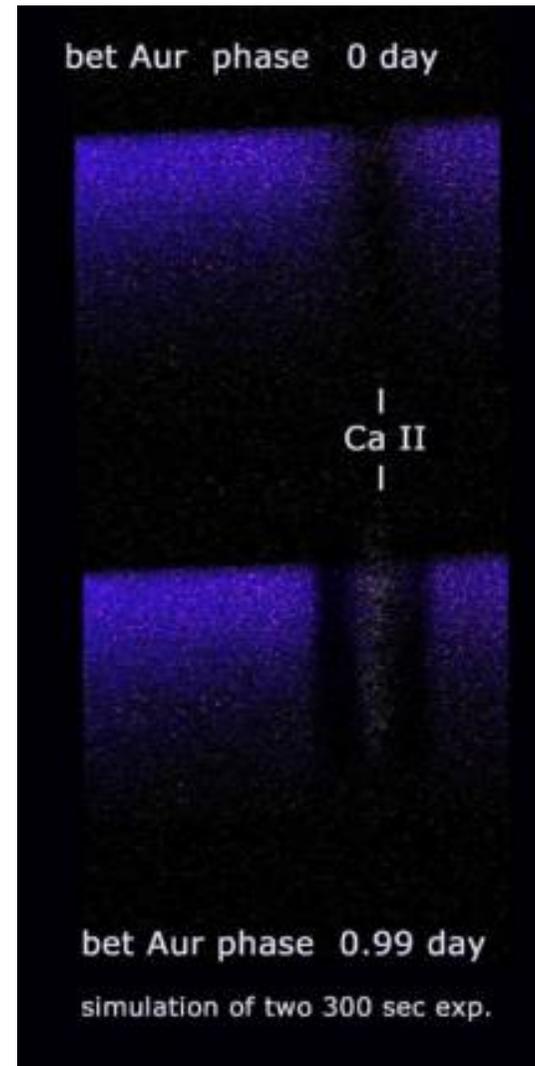


FIG. 1.—Line profiles in β Aurigae.

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System



[17] <http://www.as.wsp.krakow.pl/minicalc/>

Intermediate End of Drama

- [1] further details on our homepage: www.gemini-astronomie.de
- [2] <http://www.heavens-above.com/myth.asp?con=Aur>
- [3] first discovered and analysed in 1889 by Antonia Maury
- [4] <http://www.daviddarling.info/encyclopedia/M/Menkalinan.html>
- [5] <http://vizier-u.strasbg.fr/viz-bin/>
- [6] cf: van Zyl, J.E.: Unveiling the universe; London 1996 pp. 39 ff
- [7] Freedman, R. et al: Universe; New York 2002 pp 107ff
- [8] Struve, Otto et al. 1953 PASP 65 via internet
- [9] <http://astro.ph.unimelb.edu/>
- [10] cf: van Zyl, J.E.: p 42
- [11] the telescope store provides the grating and a manual
cf: www.baader-planetarium.de
- [12] cf: www.edmundoptics.de
- [13] will be published later on our homepage
- [14] a closer inspection of the linear dispersion results in
 $D = dx/d\lambda = 0.30 \text{ nm/mm}$ in the focal plane of the exit slit
- [15] <http://www.astronomie.de/spektrography>
- [16] construction details will soon be published on our homepage
- [17] <http://www.as.wsp.krakow.pl/minicalc/>