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Spectrographs for the Measurement of Radial Velocities

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Abstract. In this article I discuss the design of échelle spectrographs for the measurement of radial velocities. I consider the attainment of very high precision, and whether we can do still better than the current generation of instruments, and what problems have been resolved and what problems still remain to be solved in spectrograph design. The article makes special reference to the design principles followed in the Marseille-Geneva instrument ELODIE, for which the goal has been the measurement of stellar radial velocities of high precision using an R4 échelle grating.

1. Introduction

A radial-velocity measurement derives from a shift in position of spectral features at the focus of a spectrographic instrument. We do not often think about how small these shifts are. It is not generally appreciated that the accuracy to which this shift must be measured is a tiny fraction of pixel. Or, if we prefer to calculate in microns, a surprising minuteness.

What precautions should we be taking for the measurement of such small shifts? It is true that, thanks to computers, modern reduction methods allow us to correct for a wide variety of pertubations, provided that these are foreseen and understood; but such reduction procedures will give the best results if such pertubations are kept very small. We must therefore analyze the pertubations and think about how we can control them.

The correlation method initiated in its modern form by Roger Griffin, and which we developed further with an optical mask in CORAVEL twenty-one years ago and more recently with a numerical mask in ELODIE, has demonstrated its power. In terms of these methods, the problem of high precision is to improve the correlation peak. Can this be done? Does the correlation method allow us to distinguish the overall radial velocity of the object from possible distortions of the lines? This is certainly a major problem which must be resolved.

The luminous efficiency of high-precision spectrographs is low. If the use of an optical fiber with scrambling for feeding the spectrograph seems inevitable to us today, it seems to me that the transmission of this system can be considerably improved by a better choice of the F-ratio of the image beam of the telescope which is to be matched with that of the spectrograph. This problem, common to all spectrographs, could be resolved with a specialized focal-plane instrument, giving a much greater than usual F-ratio, resulting in a simplification of the spectrograph optics, hence an improvement in transmission and a serious decrease in size (which is most important in the case of high precision instruments which tend to be very large). Can we dream then, of a multiple instrument which could monitor several objects simultaneously and independently in a relatively large field?

Over the years, the introduction of CCDs has made us forget the great coudé spectrographs with extended linear fields for photographic plates; nowadays, whatever the dispersion, we must collect the information on a relatively small rectangular area. This is a big upheaval in the conception which put the échelle grating in the forefront, leading inevitably to a much more complex optical system.

A second such upheaval, as radical as the first, was the adoption of the correlation method initiated by Roger Griffin. By combining the échelle grating with the correlation method the gain in accuracy has been very clear. This CORAVEL equipment, always in service, has been functioning for 21 years on 1-m telescopes at Haute-Provence and in Chile (about 200 000 measures for 50 000 stars).

Although the échelle-grating-plus-correlation option is fundamental, let us not forget that the choices relating to reliability, stability and fidelity of the instrument are just as important.

In CORAVEL:

- there are no adjustments possible; everything is fixed, except for an oscillating blade that moves the stellar spectrum on a physical mask;
- guiding of the star on the input slit and the rotation of the dome are automated to guarantee the constancy of the illumination of the pupil.

In ELODIE[1]

We applied the same principles as in CORAVEL, but went even further:

- nothing is adjustable in the spectrograph – the assembly is final and immutable;
- nothing must move in the spectrograph, which itself is fixed and is insulated in a special chamber.

With ELODIE, we gave priority to Doppler measurements over other possible uses of the spectrograph, and we gained a factor of twenty in accuracy: 200 m/s with CORAVEL, 10 m/s with ELODIE today, 6 m/s with the sister spectrometer in Chile. These values correspond to an astonishingly small shift of the spectrum in the focal-plane of our instrument – only one three-hundredth of a pixel, which is smaller than one tenth of micron.

[1]ELODIE is the latest spectrograph designed in Marseille and then built and put into service in Haute-Provence. The two observatories, along with the Laboratoire d'Astronomie Spatiale, are once again affiliated, being part of the Gassendi Federation for Astronomy in Provence (or IGRAP)

1.1. The mechanical choices

Can one do better in sensitivity, improve the measurement of this linear displacement? I think that this would not be very easy. The equipment is compact, a parallelepiped 1.5 metres across in its largest dimension, and perhaps, we will need to increase the size in a forthcoming version. We must guarantee this sensitivity, to ensure the accuracy of the instrumentation in the face of all the risks which can make us lose a measurement. Too large a drift due to heat exchange, a bump from the turning-on of the CCD cooling system, a dome door slammed, etc. The larger the instrument the more care needs to be given to these problems. I would certainly recommend a double enclosure, the first containing the spectrograph itself in a vacuum, and mechanically isolated in a second, thermostatically-controlled chamber.

1.2. Optical choices: the fiber

The spectrograph being fixed in a specialized room, it is necessarily fed by a fiber. At the cost of a definite loss in luminosity, the fiber has significant advantages:

- with suitable precautions, a fiber makes it possible to have a stable source at the entry of the spectrograph and a stable illumination of the pupil, whatever the position of the telescope. Remember how, not so long ago, bad guiding of a star on the slit of a spectrograph (atmospheric refraction or observer falling asleep), or the dome cutting off light to the telescope, could distort a radial-velocity measurement.

- the fiber makes it possible to envisage the installation of this kind of spectrograph on any instrument. Coravels were installed on practically dedicated 1-m telescopes because it was not reasonable to install and then take down this delicate equipment for runs of 3 or 4 days. The fiber solves this problem and allows us to consider the use of this kind of instrument on the largest telescopes, the most in demand.

1.3. The optical assembly

First, let us recall the principle of the "white pupil" mounting that I described in 1972. In a classical spectrograph mounting, the camera aperture is larger than the disperser size by an amount which is proportional to the field size. As the angular field increases, it is increasingly difficult to use a large aperture for a dioptric camera; the cameras become even more complicated to design as the pupil (i.e. the grating) is far from this camera, and one must accept a considerable amount of vignetting. This limitation disappears with the white pupil mountings, where the disperser is re-imaged onto the camera and monochromatic beams intersect at the new pupil which is superimposed on the camera entrance.

Since then I have written up this design many times with numerous variations, and this white pupil mounting has since been widely used. All spectrograph designers since then have had to at least ask the question: white pupil system or not? One has to admit that the white pupil mounting, although it seems elegant and rational and allows some interesting designs, leads to much

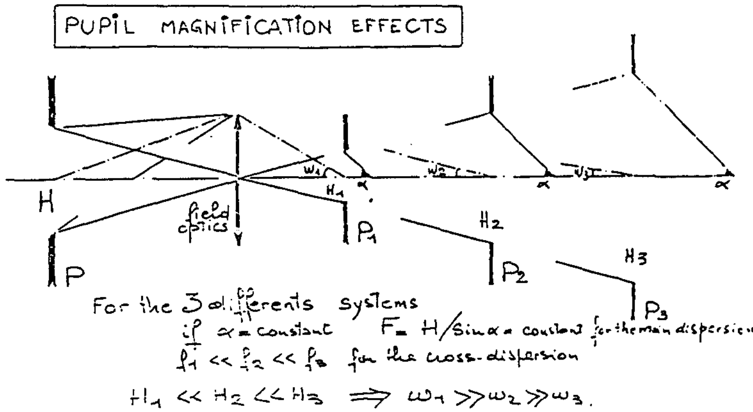

Figure 1. Pupil magnification effects. For the 3 different systems, if $\alpha =$ const., then $F = H/\sin\alpha =$ const. for the main dispersion. Also $f_1 \ll f_2 \ll f_3$ for the cross-dispersion. $H_1 \ll H_2 \ll H_3 \Rightarrow \omega_1 \gg \omega_2 \gg \omega_3$

more complex optical systems and thus to a much larger number of optical surfaces than in a classical mounting. Of course I know that somebody once said "the best optics are the most transparent, therefore no optics at all!!" This is obvious but you cannot do much with that! With modern coatings, the transparency is no longer estimated by simply counting the number of surfaces. It can be calculated accurately for each wavelength and for each thickness of the material the light goes through. For each possible design, the light losses are easy to calculate. The choice of the best design is more difficult, since the criteria are numerous and it is up to the designer to accept this responsibility, based on resolution, usable spectral range, transparency, volume and, alas, cost... Always the designer must curb his ambition somewhat and somewhere!!

If I stress the subject of the white pupil design, it is because I believe that it has one interesting property which is very little used. Between the two pupils magnification is a free parameter; in other words, there is no reason to choose two pupils of identical diameter.

Let us see how to choose this magnification. The grating giving the main dispersion is located at the first pupil (fig. 1). Let H be the diameter of this pupil P. In the vicinity of the primary spectrum at the focus of the first collimator, a field-lens system re-images P at P_1, P_2 or P_3, depending on its power. At P_1, P_2 or P_3 we place a camera with a linear aperture H_1, H_2 or H_3. H_1, H_2 and H_3 can be quite different, but if the aperture of the image beam is the same ($\sin\alpha =$ constant), the total system focal length is the same ($H/\sin\alpha =$ const.), and the main dispersion obtained is the same.

If a secondary disperser is placed in front of the camera, it is obviously the camera focal length which comes into play for the cross dispersion. It is easy to see in fig 1 that a large angular field corresponds to a small camera and vice versa: a small angular field corresponds to a camera of larger aperture. In ordinary spectrography, when a single order is observed, a large reduction is possible, the second pupil is inside the camera, and many commercial photographic objectives can be used as a model for the required camera.

In échelle spectrography, the second pupil is used and we cannot use the same procedure unless we collimate the beams a third time. In astronomy a third collimation is too penalizing for the transparency but we can enlarge the pupil, giving a smaller angular field. The "front pupil" camera objective will be all the more simple as the pupil is large. For an objective of a given complexity, the proper magnification is attained when the aberrations at the edge of the field are just barely acceptable.

In ELODIE, in spite of a largely-filled secondary pupil space we have been able to reach a reduction coefficient of 0.75, where the 100-mm pupil on the échelle grating is projected to 75 mm on the camera. It is worthwhile pointing out that such a pupil reduction leads to a reduction greater than a factor of two in the cost of the camera.

1.4. The detector: coverage of the CCD

The R4 grating used implies the use of a large number of orders, 67 in ELODIE (from the 90th to the 156th, ranging from 3906 Å to 6811 Å). The cross dispersion is done by a grism and a prism whose effects are combined so as to obtain a constant interorder spacing. Thus with comparison spectra from a thorium lamp, $2 \times 67 = 134$ orders are evenly distributed on a 25×25 mm^2 CCD with 24-μm pixels. Thus, if the CCD is used efficiently, everyone knows that with the cross dispersion given by a prism alone, the red orders (the larger ones) are very close together whereas the blue orders (the shortest) are very far from one another. Then, the CCD is very poorly used in the blue. The effect is great when the number of lines per millimeter is small (giving a lot of orders).

The difficulty lies in the elimination of the neighboring orders zero and two of the grism, orders dispersed by the prism. We can say that this and the use of an R4 grating are the only innovations of this spectrograph. The window sealing off the CCD was coated to eliminate these orders. Our bet was that we would not see any special phenomenon at the projection of the coating zone limits, and this is indeed what has happened. Over the whole spectral range used, the window has the transparency of a perfectly coated plane-parallel plate. (It is obviously of great interest to install it in the correct sense).

2. Possible improvements to our present design

Now that ELODIE has been used quite a bit at the OHP, and CORALIE in Chile, giving useful results with an accuracy limit of 10 ms^{-1} at the OHP and 6 ms^{-1} in Chile, we are encouraged to try to do better. It looks as if a gain of three to five could be achieved with equipment which will be barely more complex and expensive.

Let us review the possible points of improved performance, both in transparency and in resolution.

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2.1. Overall volume of the spectrograph and dimensions of the échelle grating

The choice of the concepts of CORAVEL and ELODIE being maintained, we will endeavour not to increase the size of ELODIE, for the reasons I have given. Having mastered the use of an R4 grating, we will not go back to using an R2, *nor will we proceed to an* R5 *since the expected improvement is too slight for* the increased difficulty.

Can we use a bigger R4? ELODIE's R4 (100 mm $\times$ 400 mm) is already a big specimen, and it is out of the question to use a mosaic because the cost increase would far exceed our budget and the gain would not be spectacular. At most, using gratings commercially available today and doing the appropriate optical calculations would allow us to increase the pupil from 100 mm to 150 mm by using a 150 mm $\times$ 400 mm grating. We can do this by increasing the collimator numerical aperture (F/10 instead of F/15) and by accepting the loss of the two crescents on either side of the pupil (since such a grating ought to have a length of 600 mm rather than 400 mm). In other words we must accept losing some light (some 20 %).

2.2. The detector

We receive 3000 Å in 67 orders on one 25 $\times$ 25 mm^2 CCD with 24-μm pixels. The projected image size of the source is 60 μm at the OHP and 50 μm in Chile, which corresponds as we have seen to an accuracy of 10 or 6 ms^{-1}. In my opinion there is a lot of improvement possible here. The image spot is less than 24 μm wide, so the projected image size should be of the same order.

The usable spectral range (i.e. the product of the CCD response by the coating transmission) could undoubtedly be larger: 5000 Å wide, from 3800 to 8800 Å. Just as it is this enlarged wavelength range would go through our objective while keeping the resolution, but would require a CCD of 33 $\times$ 33 mm^2. The use of a large CCD with 15-μm pixels seems necessary. A 50 $\times$ 50 mm^2 CCD would allow us to increase the image focal length from 300 to 400 mm, the image aperture F/3 being kept with the 150 $\times$ 400-mm R4 grating. It would be even better to use two connected CCDs, a 4k $\times$ 2k with a 2k $\times$ 2k (fig. 2). This composite CCD arangement perfectly suits the format of the échelle orders.

2.3. Spectrograph entrance (slit and slicer on fiber output)

Something must be done about the size of the projected image, because 60-μm is much too big. In all our old astronomical spectrographs, it was the width of the slit which defined the width of the projected image, not the diameter of the turbulent star. Will we be condemned to limiting the diameter of the fiber output by a slit? Actually this is not as stupid as it may seem, because at the same time as it increases the resolution it would have the additional effect of minimizing an unpleasant phenomenon due to the variable anamorphosis of échelle gratings : the image of the slit is an ellipse whose eccentricity varies strongly along a given order. As for the grating, the light loss (20% for two-thirds of the image) is not very much, but it is still a loss!!

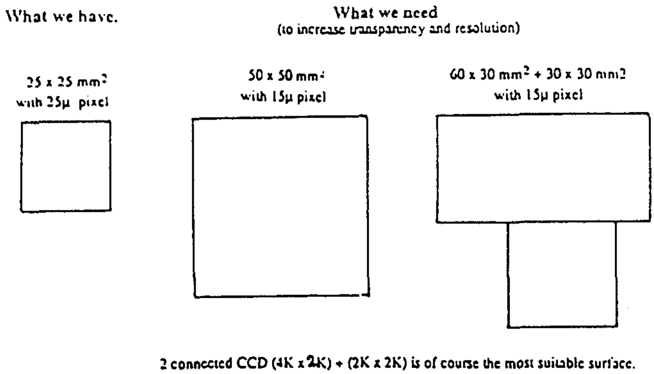
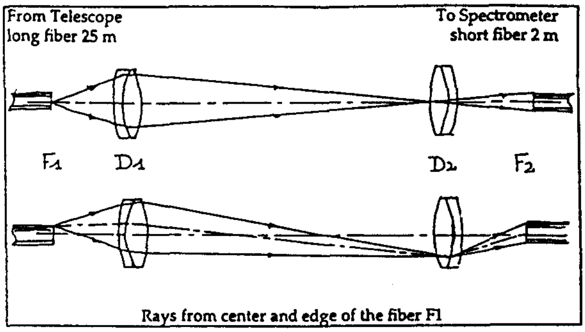


Figure 2. The detector: what we have (left) and what we need (centre and right) so as to increase throughput and resolution. Two butted CCDs provides the best solution.



- F1 is imaged on D2 by the achromat D1 with a magnification of 20
- D1 is imaged on F2 by the achromat D2 with a reduction of 20
- The configuration is symetric
- The output of the fiber F1 becomes "pupil" for F2
- Therefore, during exposures, the center to edge variation of the luminous intensity from the end of F1 is converted into angular variation of illumination at the input surface F2
- The final improvement is a uniform illumination of the collimator

NB : The scales are strongly modified for better understanding.

Actual parameters	
- Achromats D1 and D2 :	f = 10 mm Ø 6 mm
- Diameter of fibers :	Ø 100 microns
- Spacing D1 D2 :	235 mm
- Useful aperture : (input and output)	f/5
- Magnification given by the achromats :	x 21.6
Elodie Spectrometer . Mixing device	D. KOHLER OHP

Figure 3. Details of the Elodie spectrometer optical fiber scrambler

3. Innovations

In order to meet these difficulties, two innovations are under consideration. If the results are positive we will increase at the same time resolution and transparency.

3.1. Ch. Fehrenbach objective prism method (fig.4)

We can superpose a reversed spectrum onto the system of orders. The reversed orders are placed between the normal orders, in the place of the usual comparison spectrum. The two systems, obtained simultaneously be dividing the pupil parallel to the orders, results in the distance to be measured being doubled. The accuracy gain is significant. The geometry of the optics allows this procedure, but obviously the signal-to-noise ratio decreases, and much care will be needed for the calibration of the system.

One of the apparently most interesting aspects of this procedure is that although it does not correct the unpleasant anamorphosis effect previously described, this procedure symmetrizes it. I do not have any proof of this, but my vague impression is that this asymmetry may give rise to small instrumental effects not yet detected in the correlation peak. The effects would then be removed.

3.2. A possible slicer (fig.5)

It should be possible to use a slicer at the fiber exit. The "raison d'être" of a slicer depends on two criteria: it must have a higher transmission than a slit of the same resolution, and the resulting image height should not decrease the total spectral range by widening the orders. If I dared I would present a two-slice slicer of my own, because that is sufficient, but I am not a specialist and its simplicity seems suspect to me. It is a question of cutting an image of the source in half, this image being sufficiently magnified for the effects due to the cut to be negligible. One juxtaposes one semi-circle on the other and one superimposes them on a single slit with the appropriate magnification.

The resulting source and the image projected on the CCD stay the same height but have a width half of what they would be in the absence of the slicer. Obviously, there is a price to pay since Abbe or Lagrange would not tolerate this fantasy: the collimator and the camera will have twice the aperture in the direction of the height. Ray tracing show that it can be done, and what is funnier is that the required R4 grating exists at Milton Roy: a 200×400 mm^2 grating. If such a procedure has already been carried out – and its simplicity seems a proof of that – I hope that the designers will excuse me, because I never hear of such a realization.

3.3. Other possibilities

There is not enough time for me to comment on other possibilities offered by the double collimation white pupil design. For instance, a process which would make it possible to separate the blue from the red in the primary spectrum, with simultaneous observation in the two channels. Although limited by the fiber, the spectral range would be increased and the optical coatings would be much more effective in each channel.

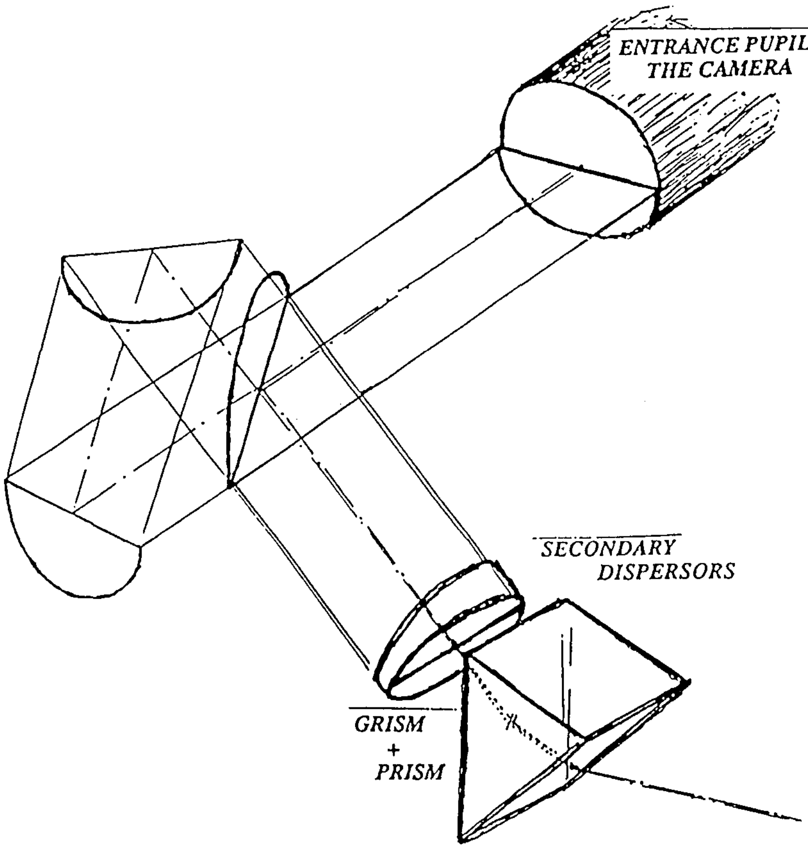


Figure 4. The Fehrenbach objective prism method. Between the secondary dispersers and the camera, the upper part of the beam is directed onto the camera by a 45° plane mirror, whereas the lower part is so directed after two reflections, and is therefore reversed. Each half of the pupil gives rise to the format of échelle orders, but one is the reverse of the other.

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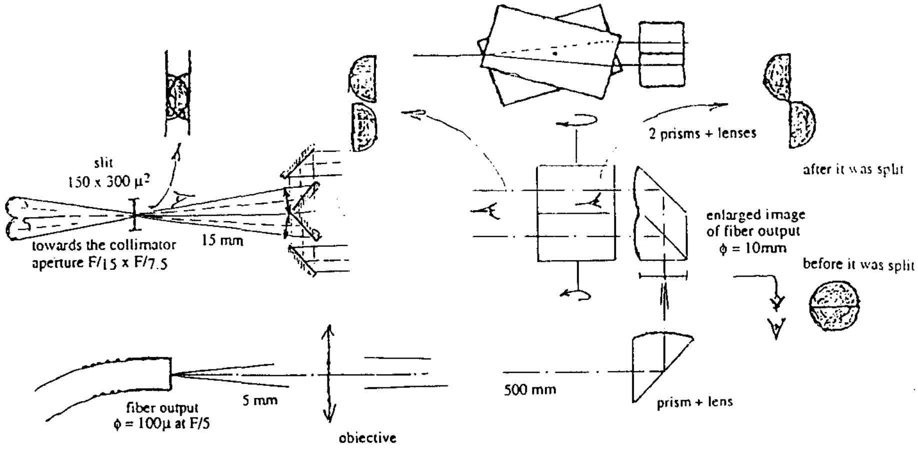

Figure 5. A slicer for Elodie. The demagnification from collimator to camera is 5 (F/15 to F/3). With this slicer we need an F/7.5 collimator and an F/1.5 camera. A gain of 1.5 in luminosity can be obtained if the transmission of the slicer is > 91 %.

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4. Telescope Focus

Finally – and this does not have much to do with the rest – I would like to say a few words about the use of bonnettes on telescopes. I can understand the use of a bonnette when it is a question of setting up whatever is needed for the correct operation of the telescope, or for interchanging a large number of auxiliary instruments. But the use of the bonnette is unhealthy in the sense that it imposes an F-ratio collimator aperture for the designer. A certain number of optical parts of the spectrograph would be more in their place upstream of the slit, where for example they would make it possible, with a corrector, to obtain a flat focal-plane and a conveniently located pupil, thus decreasing the length of a cassegrain spectrograph. In our case, a dioptric corrector with a flat focal-plane and pupil at infinity, at F/4.5, would allow us to observe several stars simultaneously. The first collimation and hence the échelle grating would be common to all the beams, and separation would be carried out in the primary spectrum. The number of stars observable simultaneously would obviously depend on the selected design.

5. Conclusion

Suppose we wanted to design an instrument more powerful than ELODIE to work at the 3.5-m ESO telescope. In order to summarize my ideas on the subject, ideas I have just presented more or less at random, here are some of my recommendations:

- compactness of the equipment, thermal and mechanical insulation, immobility – requiring use of a fiber
- immutability of the non-accessible adjustments. These characteristics are essential
- use of a 100-μm fiber with an F/4.5 input (1.3$''$ on the sky), an F/5 output, and provided with a Kohler scramble is a good choice which I cannot imagine going back on anymore than I can imagine going back on the use of the R4 grating (fig.3)
- double collimation with a Littrow mounting seems inevitable to me, but a new optical design is always possible. It seems to me that it is necessary to evolve towards a larger collimator aperture and a smaller camera aperture.
- something must be done with the output of the fiber (slit or slicer) so we can use a larger CCD with 15-μm pixels for the image.

The resolution gain is certain but we must not delude ourselves about the gain in luminosity, which depends only on the telescope's size and site and, also, on the money we will have to invest in this equipment. Nevertheless, do not forget that other schools exist with other ideas.

I would like to conclude by recalling that the new high dispersion spectrograph, ELODIE, was installed in August 1994 at the 1.93-m telescope of the Observatoire de Haute-Provence. It was the result of a collaboration between he

Marseille, Geneva and Haute-Provence observatories. It was specially designed for the best possible accuracy in the measurement of stellar radial velocities and 10 ms^{-1} has been attained. Only a year later, Mayor and Queloz announced the discovery, with this instrument, of the 51 Pegasi planet, the first known extrasolar planet.

The telescope is of moderate size and the meteorological conditions not as good as they usually are on the Pacific coast (the median seeing value at OHP is 2.5″. The cost of the instrument is relatively small $\sim$ $200 000). The discovery of 51 Pegasi demonstrates the capabilities of small telescopes if equipped with state-of-the-art instrumentation, built by a dedicated staff based on the site itself, who are therefore able constantly to adapt the new concept to the real world. Unfortunately, it seems that it is now fashionable to think that small telescopes are no longer of use when very large telescopes exist, ignoring the fact that, if large telescopes allow the observation of weaker and weaker objects, they just cannot do what small telescopes do.