THE MOST EFFICIENT TOOL FOR VERY HIGH RESOLUTION AND VERY HIGH SIGNAL TO NOISE RATIO SPECTRAL OBSERVATION OF STARS

S. Y. Jiang
Beijing Astronomical Observatory
The Academy of Sciences of China
Beijing 100080
The People's Republic of China

ABSTRACT. Today even for the most efficient spectrograph combined with a large telescope the light efficiency is only about 0.01 to 0.1 for spectral resolving power R larger than 10000 in optical wavelength band (OWB). Consequently for a very high signal to noise ratio spectral observation of rather bright stars still needs very large telescope. The main reason is that there are too many optical surface with rather low light efficiency and serious light loss at the limited slit width. In this paper we suggest a very high efficiency telescope-spectrograph system which will give an overall light efficiency varied from 0.21 at 400 nm to 0.44 at 700 nm, four fold higher than before. Using this system for R = 100000, S/N larger than 100 the limiting magnitude will be about 15.

1. INTRODUCTION

Today even for the most efficient spectrograph combined with a large telescope the light efficiency is only about 0.01 to 0.1 for spectral resolving power R larger than 10000 in OWB (Oke and Gunn, 1982). Consequently, for a very high S/N spectral observation of rather bright stars still needs very large telescope. So recent year there are many New Generation Telescope Programs in western countries. Because they are too expensive and also not very efficient, only very few mait be able stood to a real result. China have the largest population but still rather poor. We will not join such a competation but try do the best to promot the developing of astrophysics. After recognize that the main reason for low efficiency for a telescope-spectrograph system is that there are too many optical surface with rather low light efficiency and serious light loss at the limited slit width, we suggest a very high light efficiency telescope-spectrograph system as the next step for chinese astronomers after the 2.16 metres telescope.

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 15–21.

2. THE IMPORTANT FACTORS FOR CHOICE OF SYSTEM

2. 1. The Scientific Requirements

Recent astrophysics are mainly concentred on two large fields: The stellar physics and The extragalactic objects physics.

In stellar physics, to solve the evolutional problem, we must know the accurate chemical composition and atmospher condition of stars with different age, in different regions of different galaxies and stellar systems. The only reliable way of deriving atmospheric abundances of stars is the comparison of detailed theoretical models with high resolution spectrograms. We also need to know the constructions, the properties, the kinematics and the variations of the stellar winds and circumstellar mass flows for different stars. The rotation and magnetic fields also play important roles. All these can be determined from a careful analysis of its complex emission and absorption contribution to the stellar line spectrum. In some rather faraway star's spectrogram, we can find some narrow absorption lines caused by interstellar gas. We need to research there composition and kinematics. To determine the stellar radial velocities of different line system is also a common work. For all these work, we need spectral resolutions between 10000 to 100000, signal to noise ratio between 100 to 300, a broad wavelength coverage extending from 365 nm to 1100 nm, and a limiting magnitude better than 15 with a reasonable integration time.

For quasar absorption lines, we also need high spectral resolutions and high signal to noise ratio, but the limiting magnitude should be better than 20, which is very difficult to attain.

2. 2. The Sites and Seeing

Good sites is very important for high light efficiency high spectral resolution instruments. If the diameter of the seeing disk change from 2 arcseconds to 1 arcsecond the light efficiency will be double. Although there are some good sites with seeing near 1 arcsecond, for China, we will use 2 arcseconds as design parameter, and the entrance slit width will be 2.3 arcseconds to accept more than 95% light collected by telescope.

2. 3. The Dispersion Way and the Size of Echelle

For such a high resolution and wide wavelength coverage, the best dispersion way is to use echelle with prism as cross disperser. Up to now the echelle ruled by conventional techniques are limited in size up to 300 mm X 600 mm ruled area. To match such a large echelle, the cross dispersion prism will be very large and will absorb a large parts of light. So, if possible, we favour to use echelle with ruled area of 260 mm X 408 mm.

2. 4. Detector and its Size

Up to now the best detector for echelle spectrograph is CCD. The largest CCD chip will be produced in recent year will be 2000 X 2000 pixels with pixel size of 27 microns. two of them side by side will cover a field of view about 6.°2 for a camera with focal length about one metre.

2. 5. The Camera

The best camera still is the classical Schmidt type camera. To match the detector pixel size with spectral resolution larger than 100000, the focal length will be about one metre. Of course, for different objects and different work, we would better to have at least 2 camera with different focal length, and easy to change.

3. THE OPTICAL ARRANGEMENT

3. 1. The Telescope

From the theoretical point of view, for a given pixel size and total pixels of detector, under the seeing limited condition, the spectral resolution times the luminosity and the information unit number attainable in one single exposure is almost the same for any aperture of telescopes. The only problem is that if the aperture of the telescope is too small, the integration time will be too long to get enough signal to noise ratio for the faint objects. So we must make some compromise between the aperture of the telescope and the information unit number attainable in one single exposure.

If there is no any light loss within the telescope-spectrograph system, in the OWB, the monochromatic photon rates within 6 hours for a 15th magnitude A0V star will be about 40 to 300 nm cm for different wavelength. If the resolving power is 100000, the signal to noise ratio is 100, we must collect at least 2 million photons in 1 nm. So the diameter of the telescope must larger than 2.6 metres. On consider about the light loss, the smallest diameter of the telescope is 3 metres. For such a telescope, the only usable focus for high light efficiency is the F/3 prime focus of a paraboloid mirror coated with a protected silver coating which will give better than 95% reflection for wavelength longer than 400 nm and still reasonably good till 365 nm. In principle we can directly attache a very high light efficiency, high spectral resolution wide band spectrograph to the prime focus (Jiang, 1978), but on consider about the technical improvement and convenience of optical fibre, we tends to use optical fibre linking from the prime focus to a spectrograph on the stable floor.

3. 2. The Dichroic Filter and Beam Spliting

The overall wavelength coverage we intended is from 365 nm to 1100 nm. To get high light efficiency for such a wide wavelength range, the light beam coming from the primary must be splited to two beams by a dichroic filter just before the prime focus. The best dividing wavelength is about 630 nm on considering equal orders in two beams. So we have two foci: one for the wavelength shorter than 650 nm (SWB) , another for the wavelength longer than 610 nm (LWB). Putting the dicroic filter before the focus can ease the atmospheric dispersion and can make use of specific optical fibre for different wavelength band to improve the light efficiency. Because there are 40 nm overlaping on wavelength in two beams, so we can add the signals in two beams to one single signal for the same wavelength to get very high light efficiency for those wavelengths near the separation.

3.3. The Optical Fibre Linking and Image Slicer

For the F/3 prime focus, it is very easy to match with any kind of optical fibres. For the SWB, a 10 metres long FHA type fibre can give a better than 90% transmition; for the LWB, a 10 metres long QSF-ASW type fibre can give a better than 95% transmition. The field scale is about 23 arcseconds per millimeter, so a core diameter 100 microns can accept 2.3 arcseconds on the sky. For higher resolution, a special optical fibre bundle made by fibres with 20 microns core diameter is needed to act as an image slicer. If the end shape is specially made (such as square shape) for each fibre, and is thin cladding, the whole stellar image will be accepted with very low loss except the image height on the detector become about 30% higher. A Walraven type image slicer (Walraven, 1972) after a single 100 microns fibre with focal ratio enlarge micro lens is also very attractive.

3. 4. The Echelle Spectrograph

To keep the image height of the entrance slit on the CCD chip smaller than the smallest distance of two nearby orders, we suggest a ruling height of the echelle larger than half of the width of the ruled area of the echelle. For equal orders and smaller angular field of view, the rulings are 55 per mm and 31.5 per mm respectively in SWB and LWB. Both echelle are blazed at 63°.433. To ease the arrangement and changing of cameras with different focal length, it is better to choose a larger angle of construction (the angle between the incident beam and the blazing diffraction beam) which will make the blaze efficiencies and angular dispersions lower than Littrow configuration (Schroeder and Hilliard, 1980), but we can get rather smaller collimating beam size, so can use smaller prism for cross dispersion and beam widening which will have smaller light absorption. To find back the blaze efficiencies we can double the field of view in the main dispersion direction to include all the light of each wavelengths in three nearby orders and add the signal from corresponding CCD pixels to one single signal, so that for all wavelengths we get the same light efficiency as the peak efficiency in Littrow configuration. By the way we can use wider entrance slit to get higher light efficiency, and can use several pixels to share the whole light of the same wavelength to ease the saturation problem for high signal to noise ratio.

If the angle of incidence is 73°.433, then the blazed angle of diffraction is 53°.433, for a camera focal length of 1000 mm, two 2000 X 2000 pixels CCD chips with pixel size 27 microns square can cover a 6°.18 X 3°.09 angular field of view, which will include the whole wavelength band for each beam and the all light of each wavelengths within 3 nearby orders. Matching with 27 microns pixel size, the angular entrance slit width on the sky is 0.45 arcseconds, and the spectral resolving power is just 100000. Of course we need an image slicer with 5 slicers to make full use of the whole stellar light collected by the telescope. Then the total angular height of the entrance slit on the sky must larger than 12 arcseconds.

The collimeting beam size is 116 mm in diameter. For the cross dispersion of SWB, we choose a 55° apex angle prism made by KF6 glass, which will give an angular dispersion of 2°.25, and have a size about 150 mm X 150 mm X 120 mm. The output monochromatic beam size in the dispersion direction will be 120 mm which is not enough to fully use the groove height of the echelle, so we should add another KF6 prism for beam widening. If this prism is a 90° prism with an apex angle of 37°, and the incidence angle on the longest side is 67°, the output beam size for monochromatic light in the dispersion direction will be 240 mm. This prism will also produce an angular cross dispersion of 0°.9, so the total angular cross dispersion can easyly adjusted to 3°.09 which will make fully use of the CCD chip. The size of this prism will be 185 mm X 250 mm X 120 mm. T he average light path is about 180 mm for the two prism on sum, so even for 365 nm, the absorption will be less than 10%. For the LWB, we choose ZF6 glass prism to get the same cross dispersion and the same beam width. The average light path is about 150 mm, so the absorption will be smaller than 7% for any wavelengths.

The monochromatic beam size of the camera will be 243 mm in diameter. The CCD chip on the focal plan with cold finger will obstruct less than 7% incident light. The total orders for both beam are 39, so the average separation is 51 pixels on CCD chip. The smallest separation is 34 pixels. For a 2".0 seeing, we choose the real image height as 2".3, which will give an image height on the CCD chip of 5 pixels. With 5 slicers for the whole image, the total image is about 26 pixels on height, so there are still 8 pixels for sky substraction.

Some time we only need lower spectral resolution but shorter integration time or simply for fainter objects, we can change by use a camera with focal length of 250 mm, equiped with two 512 X 512 pixels CCD chips. In this case, we do not need an image slicer, so we can use 5 independent optical fibres for 5 stars to make multi objects spectral observation.

4. CONCLUSION

Our design idea is to fully use the light collected by the primary of a simple telescope. We are not only try to make the image width of the entrance slit but also the image height as small as possible. We also try to fully use the beam separation and almost loss nothing for any wavelengths. We also can fully use the diffraction light for any wavelengths fallen in different orders. The light absorption in cross dispersion prisms also is very low, so the whole light efficiency for 400 nm is 0.21, for 700 nm is 0.44. The photon events rate for all the wavelengths between these two wavelengths within 6 hours will be larger than 2 million per nm. So the limiting magnitude will be 15 for S/N = 100. This is 10 times higher than that for the coude spectrograph of AAT (Walker and Diego, 1984).

REFERENCES

Jiang, S. Y., 1978, Acta Astron. Sinica, 19, 204.
Oke, J. B., Gunn, J. E., 1982, Publ. Astron. Soc. Pacific, 94, 586.
Schroeder, D. J., Hilliard, R. L., 1980, Appleid Optics, 19, 2933.
Walker, D. D., Diego, F., 1984, in Proceeding of the IAU Colloquium No. 79: Very Large Telescopes, their Instrumentation and Programs, eds. M. H. Ulrich, K. Kjar, P. 499.
Walraven, J. H. and Th., 1972, in ESO/CERN Conference on Auxiliary Instrumentation for large telescopes, eds. S. Laustsen and A. Reiz, P. 295.

https://doi.org/10.1017/S0074180900034690 Published online by Cambridge University Press

DISCUSSION

VOGT How much order separation do you get ? My experience with prismatic cross-dispersion is that you cannot get near enough order separation with prism to have multiple objects (or multiple fibers) packed between adjacent orders.

YANG We use KF6 type glass for blue band. If the top angle is 60°. The cross angular dispersion is :
$\Delta\beta = 2 * \Delta n / (\sqrt{(4-\hbar^2)}) = 0.04649 = 2^\circ 66$ between $\lambda = 3300$ Å to $\lambda = 5461$ Å with 27 orders.
After this prism, we added another prism with top angle of 45°, so the total angular separation is about 3°8. With a focal length about 200mm, the linear separation will be 13.2mm. The smallest order separation will be about 240 micron. I think it is large enough for about 2 or 3 image with seeing disk of 2" (for more slices, you add another prism).
For red beam, we use 2F6 (SF4) type prism, it is also easy to get 3°5 angular cross dispersion. It is very important to have two or 3 beams.

RUTTEN I want to point out a major difference between solar and stellar échelle spectrometry. In solar work one does not use a crossed presisperser to put the orders side by side, but instead a parallel predisperser with slits in the predispersed spectrum, to select short segments of specific orders to be projected linearly adjacent on the detector. The best example is the Sacramento Peale échelle spectrograph.
The advantage is two fold :
(i) - data compression. You only select those spectral elements you are interested in, to fall at high dispersion on the detector wherever they are in the spectrum. For example, in a cool-star activity program we would combine the Ca II H and K lines, the Ca II IR triplet and Hα, getting the important diagnostics while not registering lots of excess data.
(ii) - multiplexing. The other detector dimension is yet available. In solar physics it is employed to measure monochromatic image detail spatially along the slit. In stellar physics it might accomodate multiple input from an image-plane fiber-coupled aperture array.

YANG Yes, you are right. But, for solar physics, the object is an extended source, and only the sun, and it is very bright. Many people observe on it frequently. So it is no special need for very wide wavelengh range record. But in stellar physics, there are too many objects, only few people observe occasionally on some specific stars, and the exposure time usually is very long. So for easily find new things, you must take a wide wavelength range record. That is the difference.