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STAR IMAGE SHAPE TRANSFORMER FOR ASTRONOMICAL SLIT SPECTROSCOPY

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RESUMEN

Presentamos un nuevo transformador de la forma de las imágenes estelares para espectroscopía astronómica de rendija que consiste de una lente plano convexa pegada a una placa rectangular plana paralela de vidrio en uno de sus lados menores con el fin de mejorar el desempeño de los sistemas espectrométricos. El sistema cambia la forma de los objetos a la forma rectangular con el propósito de llenar con luz la abertura de entrada de la rendija en los sistemas espectroscópicos. La placa se pone de lado con la lente como la abertura de entrada y la abertura de salida es la rendija iluminada vista por el sistema espectrométrico. El objetivo de este transformador es también el de mantener las características del haz de luz, la resolución intrínseca del espectrómetro y de mejorar la eficiencia de los sistemas espectrométricos y detectores.

ABSTRACT

We present a new star image shape transformer for astronomical slit spectroscopy that consists of a plano-convex lens attached to a plane-parallel rectangular glass plate on one of the small sides, with the aim of improving the performance of spectrometric systems. The system transforms the shape of the objects into a rectangular form with the purpose of filling with light the entrance slit aperture in spectroscopic systems. The plate is set sidewise with the lens as the entrance aperture and the exit aperture of the plate is the illuminated slit seen by the spectrometric system. The aim of this transformer is also to maintain the beam characteristics, the intrinsic resolution of the spectrometers and to improve the throughput of the spectrometer and detector systems.

Key Words: instrumentation: miscellaneous — stars: imaging — techniques: imaging spectroscopy — techniques: spectroscopic

1. INTRODUCTION

The main purpose of spectroscopy is to collect the maximum possible radiant power from the given source, and to disperse and detect it appropriately and efficiently. The slit spectrometers used in stellar astronomy consist of an entrance slit, a collimator, a dispersing element, a camera, and a detector. The camera is used to demagnify and focus the slit on the detector. The image produced by the optical system or telescope on the entrance slit of the spectrometers is in general not a sharp point and its size is larger than the optimum slit width. This is a common problem in astronomical spectroscopy where the stellar image is distorted by the earth atmosphere, the seeing, producing in general greater images than the required slit width. For that reason the light lost is great and is necessary to address this problem especially if one observes faint objects. For instance, if the width of the slit of the spectrometer is opened to accept, say, one second of arc in the given telescope and the seeing is of the order 2.5 seconds of arc, one is loosing fifty percent of the stellar light. Therefore, it is essential to find the way to introduce all the star light into the spectrometer. This can be accomplished by changing the shape of the image while trying to maintain the beam properties. This is realized converting the star circular image shape into a rectangular one, with the required size to maintain the resolution and to improve the throughput of the spectrometric systems.

The intrinsic resolution of spectrometers and the intensity transmitted by the slit are interconnected. Assuming perfect illumination and that the light from the source fills or overfills the spectrometer solid angle, then the resolving power, the intensity at the peak of a spectral line, and the slit width are interrelated. The maximum of the product of resolution and intensity is of the order of the wavelength of the incoming radiation times the aperture ratio of the spectrometer. This product becomes the optimum slit width of the spectrometer (Jacquinot 1954; Davis 1970; Thorne 1974) and is given by

$$w = \lambda \frac{f_s}{D_s}, \quad (1)$$

where w is the slit width, λ is the wavelength of the incoming radiation, f_s and D_s are the focal length and diameter of the collimator of the spectrometer.

To make full use of a spectroscopic instrument, the dispersion at the receptor must be matched to the resolution. The match between the size of the detector elements (pixels) and the projected slit width on the detector, based on the Nyquist criterion for discrete sampling, is that the slit width should cover two pixel, required to recover the resolution of the images, that are just resolved according to the Rayleigh criterion (Schroeder 2000).

There have been several solutions for changing the form of the circular stellar images into rectangular ones using image slicers (Bowen 1938; Richardson 1968), optical image transformers (Benesch & Strong 1951), fiber optics systems (Furenlid & Cardona 1988; Avila & Singh 2008); and some other systems for beam shaping (O'Shea 1985). In this work we propose a new system, different from the ones mentioned before, for changing the form of the stellar images to fit the entrance slit of the spectrometric systems without changing the F number of the exit beam of light in any direction with respect to the F number of the entrance beam from the telescope.

Of course, when one uses active and adaptive optics instruments in the telescope it is not necessary to have the instruments mentioned before for changing the form of the image (Lena et al. 1998; Hardy 1998). But these systems are expensive and complicated, and also, one cannot use them all the time because of the lack of useful guiding stars. The system presented here can be used in any observational situation and in any telescope-spectrometer system.

In what follows, § 2 introduces the historical background for transforming the shape of stars in spectrometric systems that sets the basics of the development of the transformer. The conception of the transformer is introduced in § 3. In § 4 the design of the transformer is described. Finally in § 5 some conclusions are presented.

2. HISTORICAL BACKGROUND

In the image slicers, the image is cut into slices, which are then arranged end-to-end to fit the entrance slit of the spectrometer system. Basically there are two types of slicers, the one designed by Bowen (1938) and the other by Richardson (1968), but there exist also several other types (Strong & Stauffer 1964; Simmons et al. 1982; Diego 1993; Suto & Takami 1997). The Bowen slicer, properly used, can result in a large advantage, especially for telescopes with large focal ratios. One of the difficulties with an image slicer is the minute scale, because the field to be sliced is very small in diameter. Benesch & Strong (1951) describe some of the problems of a Bowen slicer in an f/10 beam. The Bowen slicer is composed of a stack of glass plates, aluminized in some predesignated regions. The light is reflected by ninety degrees to align end-to-end the slices on the slit. However they are not in the same plane: they are arranged in steps like in a staircase. This is the principal reason for limiting the focal-ratio to values greater than 30 (Hunten 1974).

A modification of the Bowen slicer was introduced by (Walraven & Walraven 1972). The Bowen-Walraven image slicer in which the mirrors were replaced by total internal reflections inside a thin parallel plate where the seeing disk is sliced by a tilted edge of a prism in contact with the plate. In practice, the non-uniform illumination of the spectrograph collimator led to substantial problems and they were not extensively used.

A modified version of the Bowen-Walraven slicer that overcomes most of the problems of this type of slicers is the Confocal Image Slicer, which delivers a large number of slices, all in focus (Diego 1994). These new developments are very useful for high-resolution spectrography. These system are more complicated and difficult to construct in comparison with the transformer reported in this article.

The Richardson slicer resembles a confocal cavity composed of two concave mirrors one in front of the other. Each concave mirror is divided into two symmetric parts producing a slit between the parts. The two parts of each concave mirror are slightly tilted in opposite directions around the perpendicular to the slit. One of the concave mirrors is rotated by ninety degrees around the optical axis. In this way, the slits of each concave mirror are aligned perpendicular to each other in order to reflect the entrance image in the four inclined mirrors several times and exits through one of the slits forming a long slit with the desired size. This slicer is difficult to construct and the multiple reflections diminish the amount of light in the system. In this type of slicer all the slices are in focus.

To avoid some of the problems of the Bowen slicer in a fast system Benesch & Strong (1951) introduced an alternative, the optical image transformer, a redirector of rays. The slices are diverted to the sides by small plane mirrors, except the central one, and reflected back by concave mirrors to a central small plane mirror above or below the central slice, and are deflected through the slit. The concave mirrors refocus each slice back on the slit. In this way, there is no limitation on the focal-number of the system. The problem of many reflections and the alignment of tiny mirrors make it difficult to implement this system.

A scheme proposed by Fastie (1967) is appropriate for segmented mirror telescopes composed of several independent mirrors. The individual images may be aligned along the slit, and the pencils superposed on the grating by tiny individual prisms.

To solve the image-slicer problem Kapany (1958) suggested that a fiber optic system would help and gave a detailed exposition of that possibility but no description of a working unit was given. One can use a fiber bundle arranged in a round profile at the focal plane of a telescope and then ordered linearly in the exit of the bundle to become the entrance slit of the spectrometer. The size of the circular entrance aperture can be made to cover several seconds of arc to match the distorted star image produced by the seeing in the telescope. The exit of the fiber bundle is composed of individual fibers to form the slit with the required dimensions to be projected onto two pixels (Furenlid & Cardona 1988). This fiber bundle is very efficient and the light loses are only due to the light lost in the inter bundle holes and in the cladding of the individual fibers, and also by the absorption of light in the long fiber bundles. The individual fibers in this linear array should have a diameter that covers two pixel sizes when demagnified by the optics, as mentioned before. For a spectrometer where the magnification is $m = -1$, like in an Ebert-Fastie spectrometer, this imposes a very restrictive design parameter.

All the systems mentioned above increase the signal to noise ratio of the spectrometric system because the length of the slit is defined by the number of slices or fibers in the entrance slit of the spectrometer, thus covering more pixels in the perpendicular direction to the dispersion of the detector.

O'Shea (1985) has described several techniques to change the light distribution in one direction using cylindrical lens telescopes and the prism beam compressors that can be used in spectroscopy. The problem with these systems is that the beam becomes anamorphic, that is, they produce a beam with different divergences in two orthogonal directions. The system reported in this work overcomes most of the problems mentioned before and is introduced in the following section.

3. CONCEPTION OF THE SYSTEM

One of the objectives of the design of the shape transformer is to produce a slit with a width w and length l having the aspect ratio $r = l/w$ equal to at least six or any other desirable number. This is with the purpose of producing an image on the detector that, when projected, covers two pixels in the dispersion direction and at least twelve in the perpendicular one, that at the same time obeys the sampling theorem of Shannon and improves the signal to noise ratio, when one sums up all the pixels in the direction perpendicular to the dispersion direction. In order to take into account the imperfections, the intrinsic noise and different responses of the pixels of the detector (CCD), and the statistics of the arriving photons, it is necessary to obtain all the parameters that describe the distribution as well as the mean and the standard deviation. A Gaussian of a data set is recovered when one has more than ten values of the function, by the law of large numbers in statistics (Bevington & Robinson 2002).

The location of the shape transformer in the observational set up is shown in Figure 1, which displays the flow of light from the star to the detector passing through the telescope, the shape transformer, the demagnifying optics that forms the slit, the spectrometer, and the detector.

The simplest image shape transformer is a thin glass plate seen edgewise, which can be used to change the form of a circular image into a more or less rectangular one, shown in Figures 2 and 3 for the design and for the glass plate in the laboratory. The width w of the plate is fixed to accept the entire image that comes directly from the telescope, or from an optical fiber bundle. The light beam, after bouncing back and forth inside the plate with total internal reflections, exits on the opposite side of the plate forming an illuminated strip of length l. The form of the image is flat in the upper and lower sides of the plate and round at the sides and that becomes the slit of the spectrometer. The plate does not change the F number of the entrance beam in any direction,

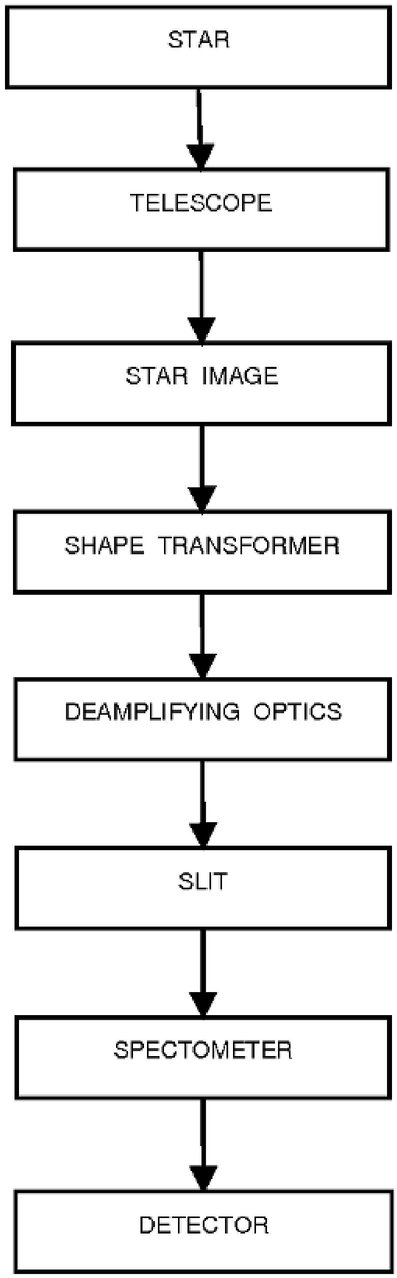

Fig. 1. The flow of light from the star to the detector, passing through the shape transformer.

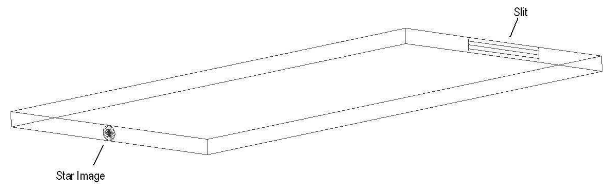

Fig. 2. Plate shape transformer showing the round entrance star image on the front face and the slit formed on the back face of the plate.

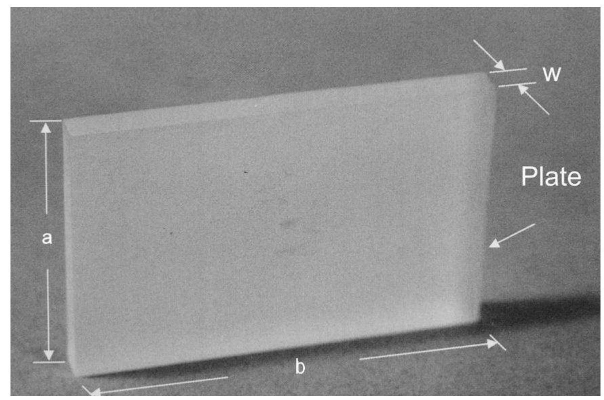

Fig. 3. Real glass plate showing the dimensions and the width w of the plate in the laboratory.

but it scrambles the light rays inside it. This system can be analyzed using the unfolding ray trace technique for plates (Cardona, Cornejo-Rodríguez, & Flores-García 2010). In order to fulfill the condition imposed by the aspect ratio given above, the plate must be large in the direction of propagation, depending on the entrance aperture ratio. This distance depends in the F number of the entrance beam of the star light produced by the telescope. The size of the image produced by a telescope is given by the plate scale in seconds of arc per millimeter as

$$s = \frac{206.265}{f(m)} \, (''\mathrm{mm}^{-1}) \, , \tag{2}$$

and the F number or focal ratio is defined as

$$F = \frac{f}{D} \, , \tag{3}$$

where f is the focal length, and D the diameter of the telescope in meters.

Equation (1) defines the width of the slit of the spectrometer when the average seeing disc of the star is given. The width in general should be larger because in order to funnel all the star light into the slit when the seeing disc of the star is larger than, say 2.5 seconds of arc. Then, for example, a telescope of 2.1 m diameter with focal ratio of 12, would produce, using equations (1) and (2), a star diameter of about 300 μm, for the seeing mentioned above. Thus, the width of the plate should have this dimensions and must be demagnified by around 7.5 times by the optics for a detector with square 20 μm pixels. The plate would be long and it would lose much light due to the distance traveled by the rays inside the plate. For this demagnification it is necessary to

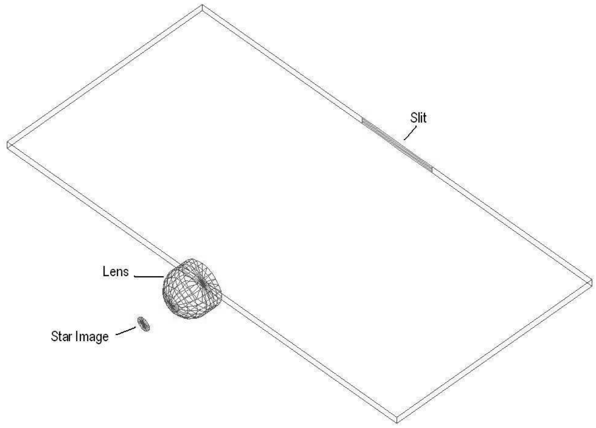

Fig. 4. Design of the shape transformer showing the star image from the telescope, the magnifying lens, the plate, and the exit slit.

employ fast cameras that, in general, are expensive and difficult to construct.

The same problems exist in a normal slit spectrometer for a slit opened to 300 μm in order to gather all the star light. For an existing spectrometer-telescope system the demagnification should not be great, because the image produced by the existing optics of the spectrometer is already used to reduce the size of the image produced by the slit, in general opened to accept star images of one second of arc, that becomes the entrance slit of the optics of the spectrometer. But the main problem is that the F number is changed and is difficult to convert back that number to the one necessary for the system. This plate can also be used with an optical fiber bundle that for the case considered here should have a diameter of 300 μm and should be connected directly to the plate. This plate does not fulfill the necessary requirements due to the problems mentioned above.

The system proposed in this work is similar to the one described before but has a small plano-convex lens attached to one of the smaller sides of the plate to overcome the problems of the single plate mentioned above. The design is shown in Figure 4. This system permits decreasing the width and the length of the plate compared to the case of the single plate.

Figure 5 shows a meridional ray trace for the system using a commercial package. The transformer is put in front of the image produced by the telescope or by an optical fiber bundle at a given distance of the lens to magnify the image to the required size and therefore the aspect ratio. The lens is used to magnify the image to give the desired aspect ratio of the slit with respect to the width of the plate, as

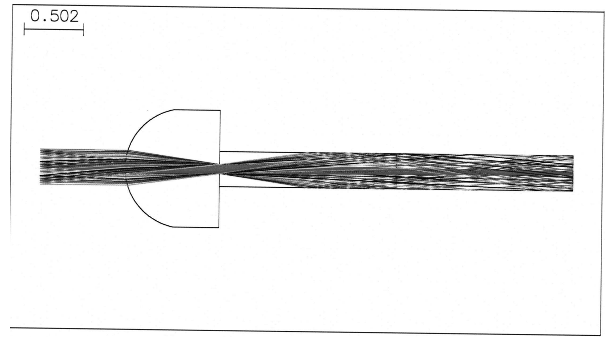

Fig. 5. Meridional ray trace of the transformer showing the waist of the beam and the internal reflections.

mentioned before; also, due to the bending of the rays by the lens the plate can be reduced in width depending on the characteristics of the lens and size of the object. The rays inside the plate are reflected between the upper and lower faces of the plate by total internal reflections; therefore, no light is lost (Figure 5) and the entrance beam F number is not changed in the plate, only its form. The light absorption in the plate is due only to the distance traveled inside of material and in this case is small.

When a wide rectangular glass plate set sidewise is used as a waveguide it behaves as an optical fiber in one dimension when the input end is one of the small sides and the light is transported inside the plate. In a fiber, from theoretical grounds, the focal ratio degradation (FRD) is proportional to the square root of the length of the fiber (Gloge 1972; Carrasco & Parry 1994; Poppett & Allington-Smith 2010). From the experimental side, the FRD slightly increases with the length of the fiber (Murphy et al. 2008). The output f-ratio for an input f-ratio of less than 5 shows little to no appreciable FRD (Murphy et al. 2008; Crause, Bershady, & Buckley 2008; Ramsey 1988). The experiments with fiber immersion show that the end effects diminish drastically the FRD for all the input f-ratios (Murphy et al. 2008). Fiber immersion involves contacting the input end of the fiber to an anti-reflective cover plate. The fiber-glass interface is made with an index matching gel.

In a plate there are no problems of macro and micro bending that produce part of the FRD in a fiber because it is a rigid piece of glass. When the length of the plate is small compared with the fibers considered in the experiments mentioned above, one expects little or no appreciable FRD. In the shape transformer, as the lens is attached to the plate it diminishes the end effects of the entrance surface of

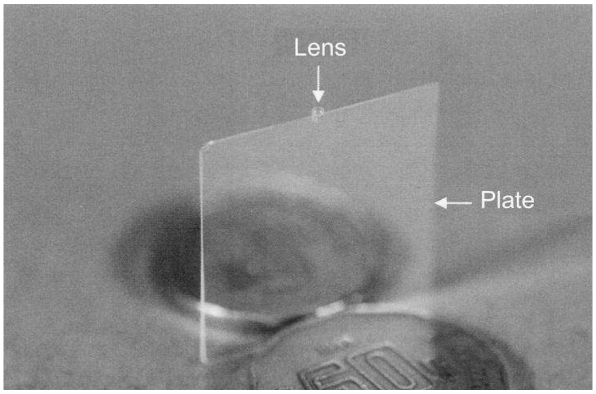

Fig. 6. Star shape transformer in the laboratory, composed of a one-millimeter diameter lens and a glass plate.

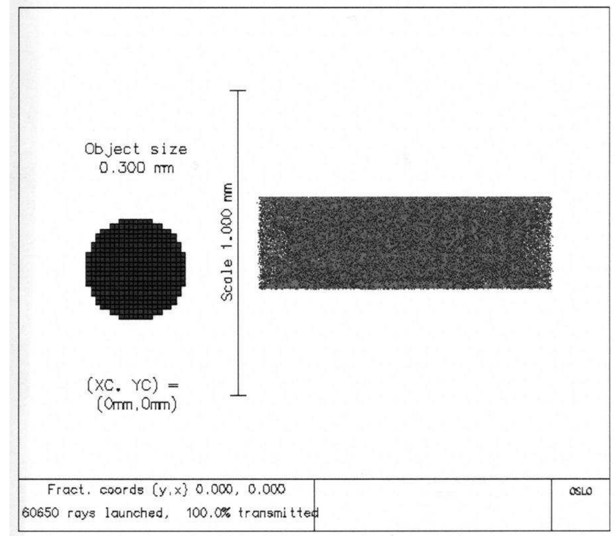

Fig. 7. Ray trace of the system for a round entrance image that produces the illuminated strip on the back side of the plate.

the plate. The lens magnifies the image of the object producing a beam faster than the beam coming from the object. The beams that enter the plate are fast and in most of the applications have an f-ratio of less than 5. Also, far from the plate the output beam that leaves the plate is symmetrical around the optical axis, showing that FRD does not occur in the plate, as can be seen in the experimental results of Flores-García (2006). Therefore, the shape transformer proposed preserves the f-ratio, as required.

If one desires a projected slit width on the detector of two pixels one has to demagnify the image of the illuminated side of the transformer maintaining the entrance F number of the original beam. To accomplish this it is necessary to magnify the image with the lens by the same amount as that of the necessary demagnification. Therefore, we fulfill all the requirements on the projected slit width, the aspect ratio of the slit, and the beam characteristics. The F number of the entrance beam to the plate is not changed inside it, and therefore the beam characteristics are not changed in the system, by the Lagrange optical invariant, since the magnification produced by the first lens is equal to the demagnification produced by the demagnifying optics. As was the case for the single plate, this system also scrambles the light rays inside the plate. Therefore this shape transformer is very efficient for astronomical spectroscopy with telescopes of any size.

4. TRANSFORMER DESIGN

We present the design of the shape transformer for some special cases in order to show the main ideas and peculiarities of the system. We have designed the transformer for a spectrometer for a $f = 8$ beam and a star image of 300 μm diameter.

The transformer is composed of a commercial plano-convex lens one millimeter in diameter and an effective focal length of 0.6 millimeters, with an index of refraction of 1.85 and a radius of curvature of the convex side of 0.51 millimeters. The plate has dimensions of five millimeters by five millimeters and a width of 0.160 millimeters, and has an index of refraction of 1.458. The lens is cemented on one of the thin sides of the plate as shown in Figure 5. Then, for a detector with 13.3 μm square pixel size, one has to demagnify the illuminated image on the side opposite to the lens on the plate (the slit of the spectrometer) by six times. For a detector with 20 μm pixel size one has to demagnify the image size by four times to fit two pixels on the detector. To maintain the beam parameters for the spectrometric system one has to magnify the image with the entrance lens by six and four times respectively for the cases given above. In the first case the image is formed on the rear face of the transformer, in the second, inside the plate. In this second case the beam of light continues traveling to the rear face of the plate forming a longer illuminated slit. For the two cases mentioned the slit length on the back of the plate will be of order of 1.8 millimeters and it will cover 22 pixels in the direction perpendicular to the dispersion of the spectrometer, for a five millimeter plate. For the second case one can use a plate of 3.38 millimeters, and therefore the length of the illuminated strip will be 1.2 millimeters in length, giving 15 pixels in the direction perpendicular to the dispersion. The demagnifying optics should be focused near the back

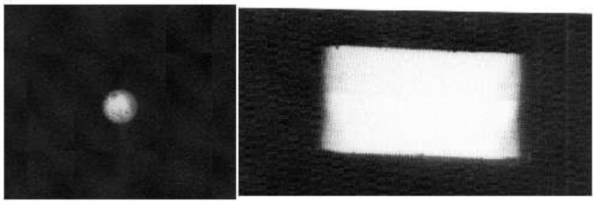

Fig. 8. The laboratory round entrance image (left) used to produce the illuminated strip (right) seen with a microscope.

side of the plate illuminated by the beam of light, in order not to show the imperfections of the rear face of the plate.

The number of pixels in the direction perpendicular to the dispersion is small, but larger than ten to have a good average, as was mentioned above, and to increase the signal to noise ratio. In the fiber bundle of 34 fibers covering 68 pixels of the Ebert-Fastie spectrometer in the direction perpendicular to the dispersion, the signal to noise ratio is large (Furenlid & Cardona 1988).

In Figure 6 we show one of the implementations of the transformer in the laboratory (Flores-García 2006). Figure 7 shows a ray trace with a commercial ray trace package for a round image as the input that produces a strip (slit) in the output. Figure 8 shows the illuminated side of the glass plate, seen in the laboratory with a microscope, produced by an illuminated circular image. Figure 9 shows the transformer with two three-mm diameter commercial lenses with focal lengths of two mm, for the demagnifying optics. This simple demagnifying optics does not absorb much light, resulting in a very efficient system.

Of course, the transformer can be changed in its dimensions and type of lens used, to be adjusted to any telescope and application, not only for astronomy. The transformer is simple and easy to construct and to implement in a laboratory, and for any telescope-spectrometer system. From the observational side, the first lens has a field of view larger than the star images, permitting the entrance of light from the surrounding sky into the spectrometer, which can be used for calibration purposes. Of course, when the light from the telescope is piped through an optical fiber bundle one encounters, as is usual, the problem of sky light subtraction. The scrambling of the light rays inside the plate makes the illumination of the slit of the transformer independent of slight changes in the position of the stars around the optical axis. Therefore, no problems of guiding the stars arise at the telescope.

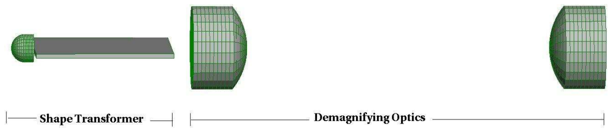

Fig. 9. Design of the shape transformer with the auxiliary demagnifying optics composed of two 3-mm diameter lenses.

5. CONCLUSIONS

We have designed a simple image shape transformer for astronomical slit spectroscopy that changes the circular images of stars into a rectangular form by using a lens and a glass plate set edgewise. The exit or back side of the plate becomes the slit for the spectrometer with the required aspect ratio for the width and length to comply with the sampling theorem and, at the same time, increases the efficiency of the spectrometric systems and the signal to noise ratio, with low light losses. The system reported here overcomes most of the problems of other systems known. This transformer is easy to construct and implement for any telescope and spectrometer system.

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