Contrib. Astron. Obs. Skalnaté Pleso **43**, 174 – 182, (2014)

Multi-mode spectrographs for small telescopes: design, operation, performances and results

U. Munari[1] and P. Valisa[2]

[1] *National Institute of Astrophysics INAF, Astron. Obs. of Padova, 36012 Asiago Italy, (E-mail: ulisse.munari@oapd.inaf.it)*

[2] *ANS Collaboration, c/o Astronomical Observatory, 36012 Asiago, Italy*

Received: November 17, 2013; Accepted: December 21, 2013

Abstract. We present three generations (Mark.I, II and III) of spectrographs we put into operation with ANS Collaboration 0.61m, 0.70m and 0.84m telescopes. These spectrographs are of the Multi-Mode type, allowing for rapid interchange between Echelle high dispersion and two separate single dispersion modes (low and medium resolution). All three modes are long-slit, rotate to any angle (including parallactic compensation for atmospheric dispersion), allow to select among different comparison lamps, and are auto-guided by TV imaging the slit, which is continuously adjustable in width and by a step decker in height. The latest Mark.III model adds many new features including remote operation, spatial splitting of order overlap in single dispersion modes, interchange between prism and grating cross-dispersion in the Echelle mode, spectropolarimetry, a coronagraphic mode and direct filtered imaging without removing the spectrograph from the Cassegrain focus.

Key words: spectrographs – optical design

1. Introduction

Spectroscopy is obviously an essential part of many astronomical investigations. As demonstrated by this Conference, a telescope of 1m-class equipped with a good spectrograph can be self-sufficient in providing the input data to support high-impact refereed papers. The same telescope, when performing only imaging/photometry, usually can provide data for similarly high-impact papers only if it is operated as part of large consortia that combine long term monitoring efforts from many different similar telescopes widely distributed in longitude. Therefore, it comes at no surprise if the recent introduction of simple, commercial spectrographs has seen many small telescopes to purchase them and venture into the field of optical spectroscopy.

In this contribution we describe our series of self-designed and self-built multi-mode slit spectrographs, evolving from Mark.I through III models, that combine into a single case permanently mounted at the telescope low-resolution, medium-resolution and Echelle high-resolution modes, allowing rapid (and in the latest version also remotely controlled) switch from one mode to another while still tracking on the target on the sky. All modes (low, medium and high resolution) are long-slit, with the slit that can be adjusted in both width and length, as well as rotated to any given angle or along the parallactic angle to compensate for the atmospheric chromatic dispersion for optimal absolute flux calibration.

That a well designed, flexible and multi-mode spectrograph can produce high-impact scientific data even on modest size telescopes is proven by the Mark.II model that in 2008 we put into operation on the 0.61m Cassegrain reflector of the Schiaparelli Observatory in Varese (on Italian pre-Alps at elevation 1200m). That instrument has so far contributed the bulk of spectroscopic data supporting 16 refereed papers (among them: Munari et al. 2008, 2010, 2011, 2013, Siviero et al. 2009, Semkov et al. 2010, Skopal et al. 2011, Raj et al. 2012, Ribeiro et al. 2013) and 43 circulars (CBET, IAUC and ATel) in five years of operation (2008 to 2013). The resulting average of 3 refereed papers and 8 circulars per year is particularly significant considering that (a) the 0.61m telescope is privately owned and operated within the ANS Collaboration[1] consortium, and (b) spectroscopic data are secured on average during only 65 partial nights per year, the rest of the observing time on the 0.61m telescope being lost to other observing programs (primarily extensive astrometric programs of minor bodies of the Solar System, and imaging confirmation or photometric follow-up of optical transients) or to bad weather.

2. Slit versus fiber-fed spectrographs

Existing commercial products, particularly for the Echelle optical combination, frequently use a single optical fiber to transfer the light from the telescope to the spectrograph. At the heart of all our Multi Mode spectrographs there is invariably a long slit, continuously adjustable in width and position angle.

While feeding the spectrograph via an optical fiber may prove advantageous in term of accuracy of the radial velocities (the spectrograph does not move with the telescope and the fiber end facing the collimator is evenly illuminated no matter how the light enters the other end of the fiber attached to the telescope), it suffers from several drawbacks: (1) a single optical fiber requires a second, equally long exposure to record the sky background to be subtracted from the science exposure, effectively doubling the exposure time to observe a given object. The fainter the science target, the more critical the subtraction of the sky background. The sky continuously changes because of dawn/dusk progression, rise/setting of the Moon, variable sky transparency, change in airmass, etc. A long slit permits the simultaneous recording of the sky and the science target and therefore allows proper background subtraction; (2) an optical fiber has a fixed aperture, which cannot be adjusted to best match the brightness of the target and the seeing conditions; (3) spatially resolved emission around a stellar object or observations of extended objects like planetary nebulae, galax-

[1] http://www.ans-collaboration.org/

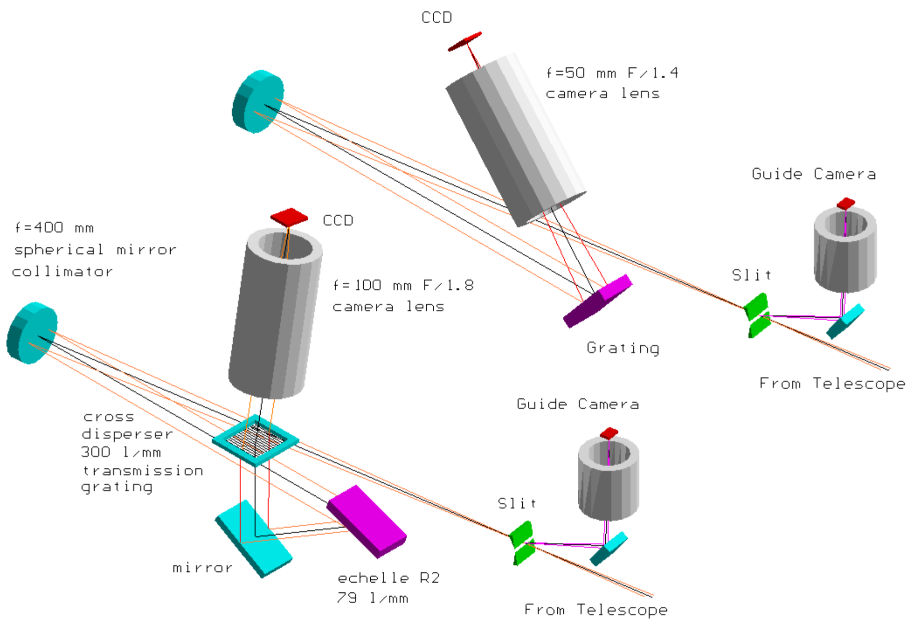

Figure 1. Optical layout of Mark.II spectrograph in the single dispersion (above) and Echelle (below) modes.

ies, comets etc. requires a long slit that can be rotated to the desired angle to simultaneously record the whole angular extension of the target and the sky background beyond it; (4) the differential atmospheric refraction spreads the incoming light from a star into a chromatically dispersed figure, aligned along the parallactic angle, whose angular extension depends on the range of wavelengths and the airmass. Low on the horizon its angular extent widens well beyond the fixed, small aperture of an optical fiber. To avoid losing flux at the ends of the observed range and to achieve correct flux calibration, a slit rotated to the parallactic angle is required; (5) the transmission through a fiber nulls the polarimetric signature of an input signal, while the slit preserves it. Therefore, a fiber-fed spectrograph would need a polarimetric module separated from the rest and placed at the telescope *ahead* of the optical fiber.

3. The Mark.II version of the Multi-Mode spectrograph

Version Mark.II of the Multi-Mode spectrograph went into operation at the Varese 0.61m telescope during 2008, when it replaced the previous Mark.I in-

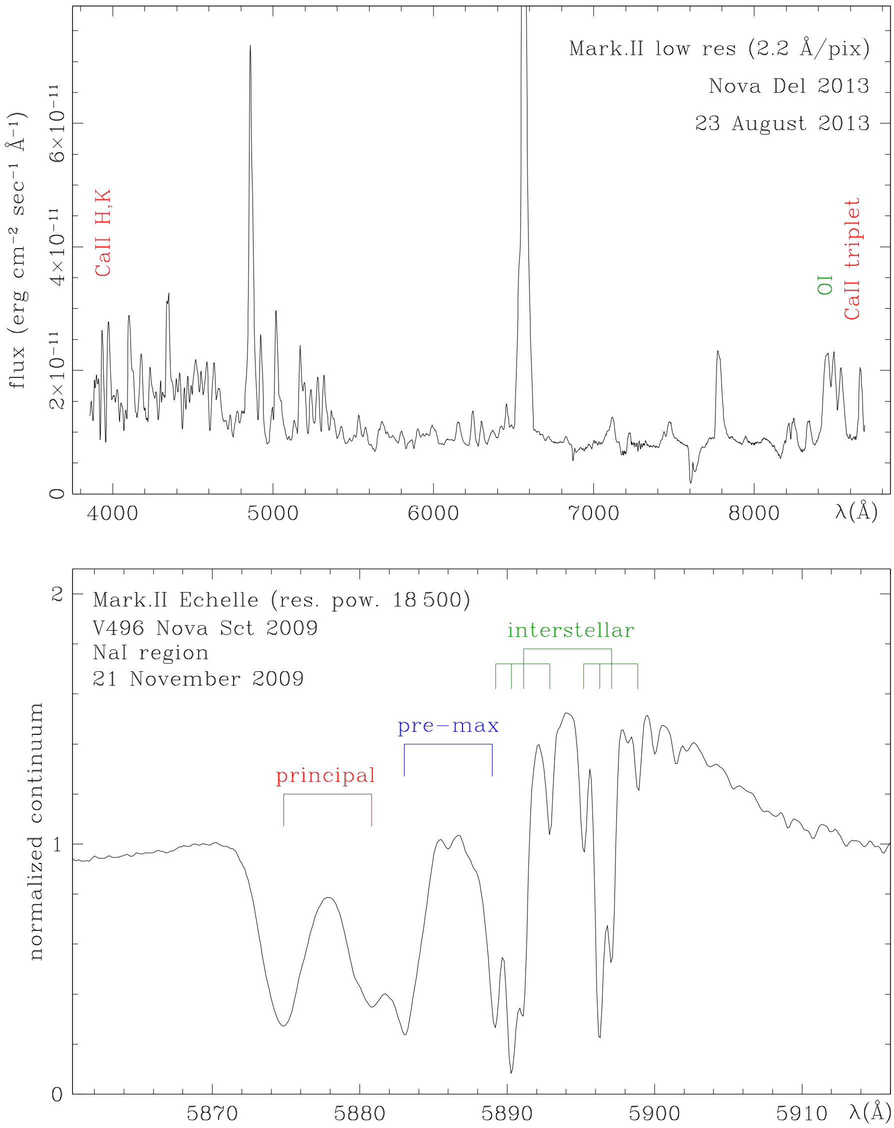

Figure 2. Examples of a complete low-res spectrum (above) and of a small portion of an Echelle spectrum (below) obtained with the Mark.II Multi-Mode spectrograph on the Varese 0.61m telescope, to highlight spectral coverage and resolution.

strument, which was later moved to the Polse di Cougnes 0.70m telescope, which is also part of the ANS Collaboration consortium, and where it is still in regular use (see Cetrulo et al., these proceedings). In order to obtain the maximum performance at the lowest cost, in bulding our spectrographs we (a) used only off-the-shelf commercially available lenses, mirrors and gratings and standard photographic lenses as camera optics, (b) invested great effort in accurately design and optimizing the optics and mechanics, and (c) machined and assembled all parts at home during spare time. The Mark.II delivers low resolution spectra at 2.2 Å/pix scale that cover in one shot the whole 3900-8670 Å interval (adjustable by rotation of the 600 ln/mm grating) with a spectral PSF of 2.1 pix (resolving power of 1400 at Hα) for a slit width of 2.5 arcsec. The length of the slit is 3.5 arcmin, and the spatial scale perpendicular to dispersion is 0.91 arcsec/pix. The medium resolution spectra are recorded at 0.75 Å/pix (resolving power 4100 at Hα for a spectral PSF of 2.1 pix) and cover a range of 1640 Å that can be shifted in lambda by rotating the 1200 ln/mm grating. The Echelle mode records in 31 orders and no gaps the whole 3900-8640 Å range, at a resolving power of 18 500 for a 2.0 arcsec slit width and 1$\times$1 binning (12 000 for a 2.0 arcsec slit and 2$\times$2 binning, 10 000 for a 3.0 arcsec slit and 2$\times$2 binning), with a minimum free slit height of 20 arcsec at the bluest orders.

The telescope focal ratio is f/20. A longer focal ratio means (a) a larger image scale onto the slit (in this case 2 arcsec=120μm) which can be machined to lower tolerances, and that (b) a spherical mirror can be used instead of an expensive off-axis paraboloid, because the astigmatism introduced by the spherical mirror is minimal and can be aligned along the spatial direction and perpendicularly to spectral dispersion, thus eliminating any loss in the amount of collected light and in the spectral resolution. In fact, considering that the off-axis angle between the entering beam and the beam reflected by the collimator toward the gratings is ϑ=5°, the resulting astigmatism (measured as the least confusion circle diameter, e.g. Schroeder, D., 1985) is AAS=ϑ/2F = 76 μm, far less than the typical value of slit width (120 to 180 μm $\approx$2 to 3 arcsec). A filter can be inserted in the collimated beam for suppression of order overlaps before the beam reaches the grating. Gratings are mounted on pre-aligned cylindrical supports that can be fast and easily interchanged to obtain low, medium or Echelle dispersion spectra. Low and medium dispersion gratings can be rotated to adjust the spectral range, and a similar function is performed by the cross-disperser of the Echelle optical assembly. The optical assembly of the Mark.II spectrograph is presented in Figure 1.

Low dispersion is obtained with a 600 ln/mm reflection grating working at the first order, that covers the full 3900-8670 Å interval with a SBIG ST10XME camera (KAF-3200ME chip, 2192$\times$1472 array, square 6.8 μm pixels), from [Ne III] 3969 Å and Ca II H & K 3967, 3933 Å in the blue, to OI 8446 Å, CaII 8498, 8542, 8662 Å and hydrogen Paschen 15, 16 in the far red (cf Figure 2). The 600 ln/mm grating is set to work far from Littrow configuration, with incident angle α=40° and diffraction angle β=−15°. This results in anamorphic magnification $cos(\beta)/cos(\alpha)$ = 1.26 that adds to the ratio of the focal lengths of collimator (400 mm) and camera (50 mm) for a total 10$\times$ image reduction from slit to

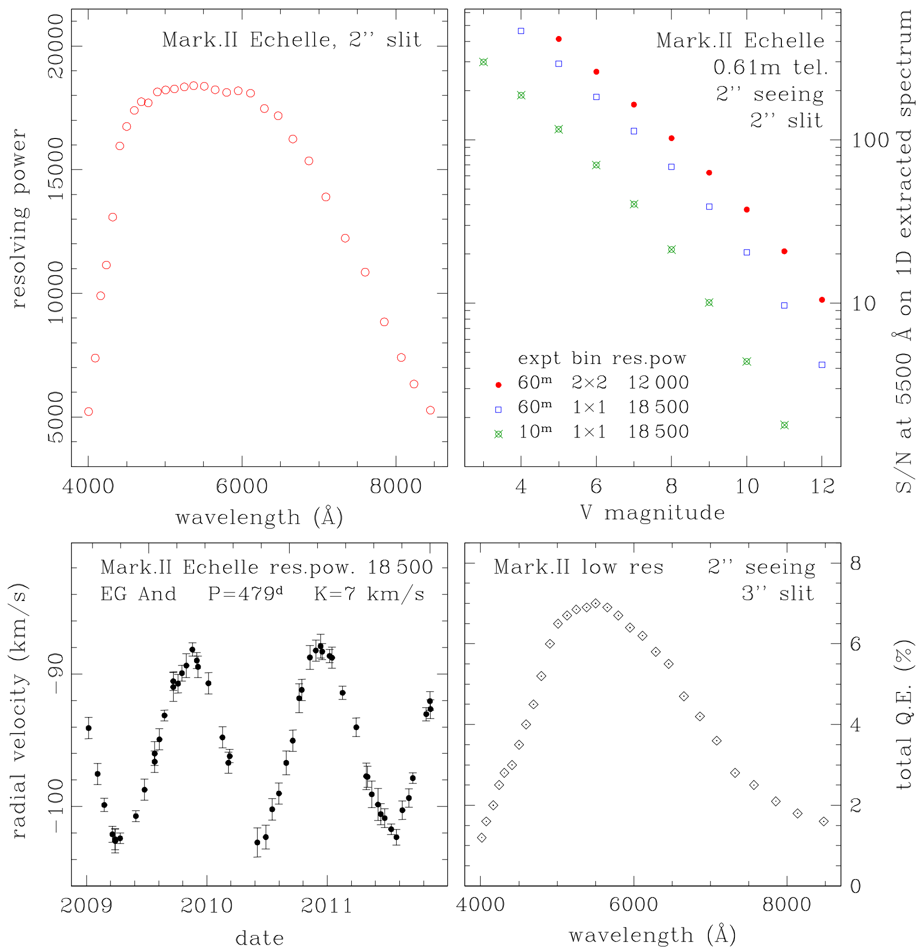

Figure 3. Examples of Mark.II spectrograph performances. *Top left*: Resolving power, measured as λ/FWHM of unblended absorption lines on the spectrum of a K2III red–clump star (average of center, blue and red ends for each Echelle order). *Top right*: S/N for various Echelle combinations. *Bottom left:* Orbital motion recorded for the symbiotic star EG And. *Bottom right:* measured quantum efficiency of the low-res mode.

CCD and an optimal image scale of 0.91 arcsec /pixel. Medium dispersion is obtained with a 1200 ln/mm reflection grating working at first order. Around Hα this grating operates at incident angle α=$-1°$ and diffraction angle β=$-51°$, $cos(\beta)/cos(\alpha)$ = 0.63 for a dispersion of 0.75 Å/pix. The camera lens for both the 600 and 1200 ln/mm gratings is a Minolta 50mm f/1.4.

Low cost R2 Echelle gratings are available up to a size of 25×50 mm. Doubling the size of the grating is ∼10× more expensive, so we decided to limit the pupil diameter at the grating to 20 mm. In Echelle mode, the parallel beam from the collimator reaches first a 79 ln/mm Echelle (R2) grating and then a 300 ln/mm transmission grating (AR coated, with 75% peak efficiency at 5500 Å) for cross dispersion of the Echelle orders from 26 to 56. Order separation ranges from 100 pix for the two reddest orders (corresponding to 75 arcsec), to 30 pix (20 arcsec) at the bluest two. Order overlap is avoided by a movable decker that allows different slit heights to be selected. A 100mm f/2 Canon lens images the Echelle spectrum onto the CCD, with cross dispersion aligned along the longer side of the chip. The Echelle grating works away from Littrow configuration, the angle between incident and diffracted beam being 14°. This gives an anamorphic magnification of 1.65 at the expense of 10% overfilling of the grating and of a 35% loss in peak intensity of the blaze function. This 35% loss is compensated by a broader efficiency profile along the Echelle orders, higher than the Littrow blaze function at the edges of the free spectral range. This allows a more uniform performance of the instrument over all wavelengths. Echelle anamorphic magnification adds to the ratio of the focal lengths of collimator (400 mm) and camera (100 mm) for a total 6.6× image reduction from slit to CCD with a scale of 0.75 arcsec/pixel onto the CCD. Spectral resolution with 2 arcsec slit (see Figure 3) is constant around 18 500 from 4500 to 6500 Å and decreases towards both ends of the spectral range because of the chromatism of the commercial photographic lens used as a camera. Commercial photographic lenses, designed for visible operation, have good transmission only longword of 3900 Å and an achromatic imaging restricted between 4300 and 6500 Å.

Three selectable wavelength calibration lamps are available. A Th[Ar] hollow cathode lamp (operated at 10 mA) is used for Echelle spectra. Strong Ar lines redward of 6900 Å are weakened using a Corning 4-69 filter. A pair of Ne and Ar lamps are used for low and medium dispersions. The lamps are focused with an aspheric f/2 condenser lens onto a 1 mm core plastic optical fiber. The fiber transfers the light to the spectrometer, where a lens focuses it evenly onto the slit with a beam converging at the same f/20 ratio of the telescope.

The spectrograph is enclosed in a rigid aluminum box that can be rotated around the telescope optical axis for slit orientation on the sky (for ex. along the parallactic angle). The optical path is folded twice with flat mirrors, because there is not enough room for an on-axis optical configuration given the low fork clearance at the Cassegrain focus of the 0.61m telescope.

The slit is mounted on a micrometric stage and can be opened continuously from zero to some millimeters, even if usual range of operation goes from 120 μm (2 arcsec) to 210 μm (3.5 arcsec). The slit is built from mirrored inox steel and it is tilted by 10°, reflecting onto a TV camera (Watec 120N) for field recognition and auto-guiding. The area imaged by the guide camera is 4.5×3 arc minutes.

Figure 2 shows some sample spectra taken with the Mark.II spectrograph mounted on the Varese 0.61m telescope, to highlight the spectral coverage of the low-res mode (from CaII H&K to CaII triplet) and the resolving power of the Echelle mode. Figure 3 highlights some of the performances of Mark.II spectrograph on the Varese 0.61m telescope: resolving power measured on each individual Echelle order, S/N as a function of magnitude/exposure time/observing mode, total quantum efficiency (Q.E.) of the spectrograph operated in low-res mode, and an example of long term stability in the zero point of radial velocities as inferred from 3-yr long orbital monitoring of the low amplitude symbiotic binary EG And. The *external* error of Echelle radial velocities (0.7 km/s) for the Mark.II spectrograph, derived from hundreds of observations of IAU standard stars, and the performance of these Echelle spectra in supporting the derivation of stellar temperature, gravity and metallicity is discussed by Milani et al. (these proceedings).

4. The new Mark.III version of Multi Mode spectrograph

The valuable scientific return of the Mark.II spectrograph mounted on the Varese 0.61m telescope, suggested to develop a improved version of the spectrograph for the new 0.84m telescope that has just been opened at the same observing site in Varese.

The new Mark.III version of Multi Mode spectrograph is ready to be mounted at the telescope to begin the commissioning and then the science validation phase, while normal operations are expected to start during the spring of 2014. While pursuing the same concept of previous models (rapid switching among low-resolution, medium resolution and Echelle high resolution modes), the new Mark.III improves on the throughput (by eliminating folding mirrors and replacing trasmission grating in cross dispersion with a 60° SF11 prism) and operational efficiency, and add a broad array of entirely new modular features, which are discussed in detail by Munari and Valisa (2014, which is the Mark.III documentation paper). The main new features are: (a) the nightly operations - including the change from one observing mode to the other - can now be controlled remotely with no need for the observer to physically access the dome and the telescope; (b) removal by spatial splitting of the spectral overlap plaguing single dispersion modes, and therefore not only curing the consequent spectral confusion, but also improving the accuracy of absolute flux calibration of the red part of the spectra; (c) the possibility to change rapidly from a prism to a VPH grating to perform the cross-dispersion of the Echelle orders. In addition to many other optimization opportunities, this switch allows to observe at the same resolving power of GAIA (11 500) the whole 8400-8800 Å range over which this cornerstone mission - soon to be launched by the European Space Agency - is expected to collect spectra for $\sim$50 million stars in 5 years over the whole sky, generating an endless stream of follow-up opportunities for ground-based telescopes. Spectra (at a resolving power 7 500) over the same GAIA region have been already obtained for half a million southern stars by the RAVE ground-based survey (Kordopatis et al. 2013); (d) the possibility to perform spectropolarimetry in combination with any of the available observing modes (low-res, medium-res and Echelle); (e) a coronagraphic mode to occult the stellar seeing disk of a star and to safely expose on feeble nearby background features; and finally (f) the possibility to perform direct imaging with photometric filters without removing the spectrograph from the Cassegrain focus.

Some participants at this Conference have warmly invited us to consider the possibility to build (simplified) copies of the Mark.III spectrograph for other Observatories. Following on this suggestions, we have adapted the optical and mechanical designs to a modular approach and passed them to an opto-mechanical factory[2] that should soon start manufacturing the spectrograph.

References

Kordopatis, G. et al.: 2013, *Astron. J.* **146**, 134
Munari, U., et al.: 2008, *Astron. Astrophys.* **492**, 145
Munari, U., et al.: 2010, *Publ. Astron. Soc. Pac.* **122**, 898
Munari, U., et al.: 2011, *Mon. Not. R. Astron. Soc.* **410**, L52
Munari, U., et al.: 2013, *Mon. Not. R. Astron. Soc.* **435**, 771
Munari, U., Valisa, P.: 2014, *Publ. Astron. Soc. Pac.* , to be submitted
Raj, A., et al.: 2012, *Mon. Not. R. Astron. Soc.* **425**, 2576
Ribeiro, V.A.R.M., et al.: 2013, *Astrophys. J.* **768**, 49
Schroeder, D.: 1987, *Astronomical Optics*, Academic Press Inc., San Diego California
Semkov, E., et al.: 2010, *Astron. Astrophys.* **523**, L3
Siviero, A., et al.: 2009, *Mon. Not. R. Astron. Soc.* **399**, 2139
Skopal, A., et al.: 2011, *Astron. Astrophys.* **536**, A27

[2]http://www.afsofting.it/spectrograph.php