AN ACOUSTO-OPTICAL SPECTRAL IMAGER FOR ASTROPHYSICAL OBSERVATIONS

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The results of tests of acousto-optical imaging spectrometer with the CCD camera for astronomical observations are presented. The geometry of acousto-optical interaction and design of acousto-optical filter based on a TeO_2 single crystal is discussed. The acousto-optical filter with a 13Å pass band operates in the wavelength range λ 6300-11 000Å. The image spectra for the planetary nebula NGC 7027 in the Hα line and for Saturn in the methane absorption band are obtained.

Introduction

In early 1970's the rapid variability of the Hα emission line in nucleus of the Seyfert halaxy NGC 4151 with a time delay relative to continuum variability was discovered [1, 2]. The detection of a similar effect in 1984 with a smaller lag, in the C IV line [3] and establishing in 1986 [4] the phenomenon that lines of different ionizations had different lags relative to continuum variability, provide the new trend in the studies of active galactic nuclei (AGNs) - echo mapping i.e., obtaining the spatial distribution of various elements. The first observations were carried out with a wedge interference filter [5]. Photometric observations with a wedge filter allow to use small telescopes with high measurement accuracy. However the transmission of wedge interference filters is low. At the same time, it is difficult to use conventional (nonwedge) interference filters in investigating emission-line variability in AGNs because of their redshift: each object requires its own set of filters.

In late 1960's - early 1970's, a new class of spectral devices was devised - electronically tunable acousto-optical filters (AOFs) [6]. In the mid-1970's the first attempts to use tunable AOFs for astronomical spectroscopic observations were made: at the Harvard Observatory in 1976 [7] and at the Royal Greenwich Observatory in 1984 [8]. AOFs at that time were imperfect. Thus, a collinear filter based on the $CaMoO_4$ single crystal was used in the imaging spectrometer [7]. The filter had a small optical aperture (4x4 mm) and a large length (~50 mm). Cylindrical lenses were used to compensate astigmatism. A special optical system to pass the image of an object through such a filter was required. These factors limited angular and spatial resolutions of the system. The filter based on the TeO_2 single crystal [8] also had non-optimal design. It had a very small angular aperture (~0 .4^o) apart from a small optical aperture (3x5 mm) that made it impossible to select high spatial frequencies.

The first paper that showed a high quality of spectral acousto-optical instrumentation intended for astrophysics was published in 1991 [9]. The NASA provided AOFs of various designs. The wide-angle noncollinear paratellurite filter with large optical aperture (14x16 mm) and high spatial (100 lines per mm) resolution was the most promising among the filters.

The acousto-optical imaging spectrometer.

Last years, the efforts of researches have gone into creating a new line of AOFs designed for the spectral analysis of optical images. Several specific requirements are imposed on filters for spectral analysis of images: they must have large angular field of view, they have to be capable for efficient filtering of high spatial frequencies in images and combining high spatial resolution with a high spectral resolution [10, 11, 12]. Unique imaging spectrometer based on the tunable acousto-optical filter for acquisition of data combining simultaneously both high spatial resolution and high spectral resolution was recently designed in the Acousto-Optical Research Center [13]. The spectrometer is intended mostly to study planets and emission objects to get images at different wavelengths. The device can be useful to study the variability of emission lines in AGNs (active galactic nuclei), such as Seyfert galaxies and quasars. The spectrometer possesses very large optical input aperture (15x17 mm) and optical angular aperture about 7^o. Non-collinear acousto-optic interaction in TeO_2 single crystal is used in AOF. The crystal cut angle is equal to 11^o. The tuning spectral range λ 6300-11000Å corresponds to the range of control frequencies 133-67 MHz. The light input polarization corresponds to the ordinary ray. Special optical geometry of the acousto-optical filter is used in order to keep the direction of the optical axis the same. The filter exit face makes an angle of 4.3° with the entrance face. In this case, the diffracted extraordinary beam propagates collinearly with the incident beam after its refraction on the exit face. Additionally, the spectral image displacement on the CCD matrix at different wavelengths is partly compensated. These constructive features of the device provide easy way for its installation into the telescope because the complicated additional optics is not needed (Fig.1). The spectrometer can be used with any typical f/12 – f/20 Cassegrain telescope and with any typical CCD camera.

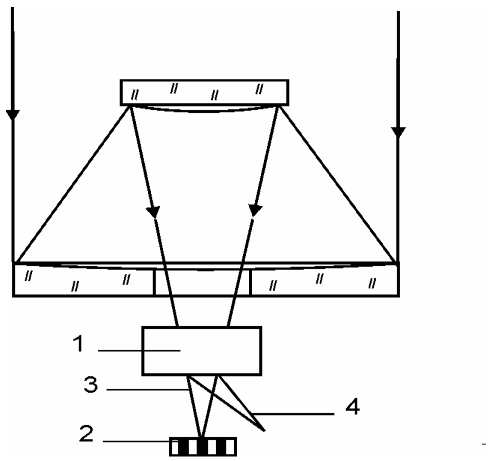

Fig.1. Scheme of AOF installation. 1- AOF, 2- CCD camera, 3 – diffracted beam, 4- zero-order beam.

Discrete resistive acoustic-field apodization was used in filter for the first time, and that allowed to reduce the level of spurious side maxima of the transmission function to -17 dB. Resistive apodization arouses the peculiarities of the electrical impedance matching. After an appropriate modification phenomenological method [14] was used for the matching. The filter's transducer impedance was matched in a frequency range exceeding an octave: 65-140 MHz with a VSWR no worse than 2.5. The diffraction efficiency for linear polarization is 80%, control RF power at wavelength 6328Å is 1.7 W. The filter spectral transmission curve at λ 6431Å was obtained in the laboratory by direct measurements with a white-light source. The filter pass bandwidth at –3 dB level (FWHM) is 13Å.

The flowchart of the electronic AOF control device is shown in Fig.2.The device is made of two separate modules. The controller card complies with the PCI bus standard and is plugged into any free PCI slot. The high-frequency power amplifier is placed in the CD-ROM case and is located in one of the corresponding compartments in the PC cabinet. The controller card interface with the PCI bus of the PC and with the card internal bus is implemented on PLIC. A frequency grid for AOF control is generated by a digitally tunable oscillator (DTO). Fourteen of the 32 accessible bus bits are used for frequency control. This allows 16 384 frequencies to be generated. The same 14 bits (in the DTO module, different registers and control channels for frequencies and amplitudes) are used to control the output oscillator amplitude, which yields a depth of the output signal control in amplitude no less than -55 dB. One of the DTO channels was introduced in the device to determine the AOF temperature and temperature drifts in DTO frequency circuits. The acousto-optical cell temperature was measured by a DS18S20 sensor over a single-wire line (the MicroLAN standard). The software for the controller card includes a library (DLL) program to work with the card in the WINDOWS 95/98 operating environment and an interface to work with the telescope. The presence of two control channels makes possible to set two working wavelengths (e.g., an emission line and continuum), switched by the computer.

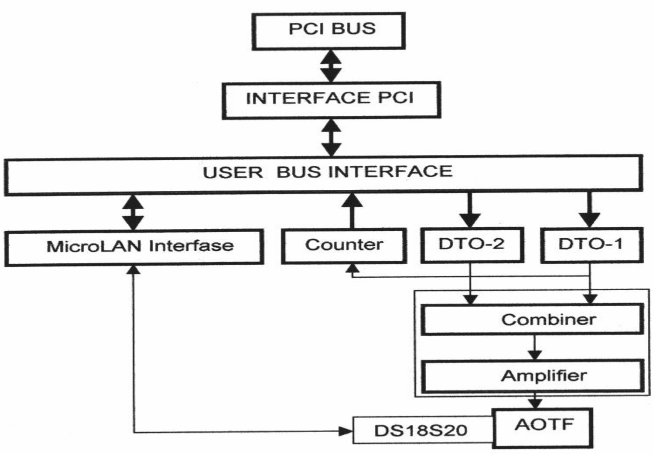

Fig.2. A flowchart of the AOFs electronic control system.

Observations

The imaging acousto-optical spectrometer was tested with the ST-6 CCD camera. The planetary nebula, the star, Saturn and Jupiter were observed. The observations were carried out at the Cassegrain focus of a 60-cm (Zeiss-600) telescope. The filter was placed in a convergent beam (1:12.5) at such a distance from the detector that the zero-order ray definitely did not fall on the matrix. No additional optics was used. The detector was the ST-6 CCD camera (375x241 pixels). The pixel size was 23x27μm.

We set the following objectives: to determine the resolution of the spectrometer with an AOF; to obtain the filter transmission profile for comparison with the laboratory profile; to determine the possible optical distortions introduced by the filter; and to perform test observations of AGNs with various redshifts.

To determine the spatial resolution of the tunable AOF we obtained images of the seeing disk of the star Vega (α Lyr) with the AOF at λ 6300Å and with out the filter, but with a neutral V -band filter (λ_{eff}=5500Å) in order that the exposure time was of the same order of magnitude. We found that the AOF distorted the seeing disk only slightly: the diameter of the star seeing disk is 2.5±0.1 arcsec with the AOF and 2.1±0 .2 arcsec with the neutral filter (see Fig.3). We can state the spatial resolution of the spectrometer is about 1arcsec. Faint vertical tracks in Fig.3 in the diffraction plane originated from the sidelobes of the transmission function.

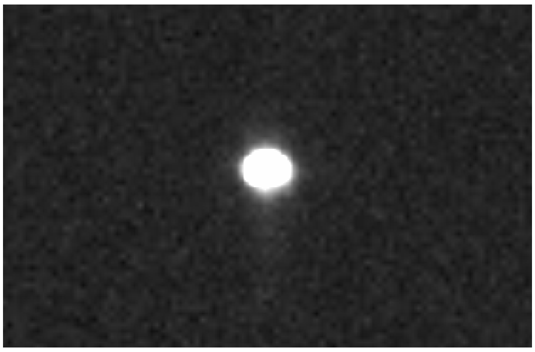

Fig.3. The image of the turbulent seeing disk of the star Vega.

We observed the planetary nebula NGC7027 near the Hα emission line also. The filter transmission profile is recorded almost completely, because the Hα width in this nebula is ~0.3Å. The nebula NGC 7027 is most suitable for this purpose: this is one of the brightest star-like nebulae, 18″×11″ in size. Fig. 4 shows the Hα region scanned at 2Å steps. Each exposure was 2 min long with the average background (moonless sky) being 17.9±0.3 counts per pixel (ADU); the rms deviation was 2.5.

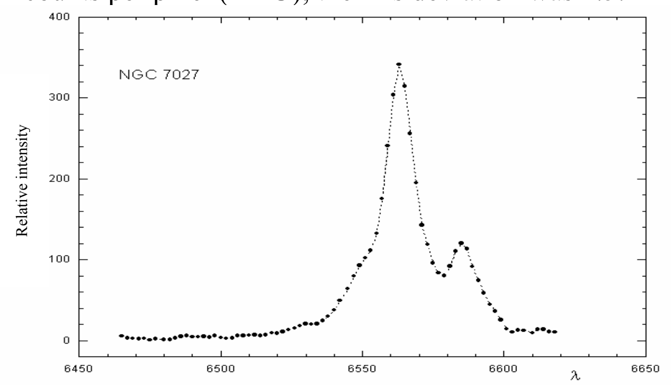

Fig.4. The Hα (λ 6563Å) line: peak on the right corresponds to the [NII] λ 6584Å.

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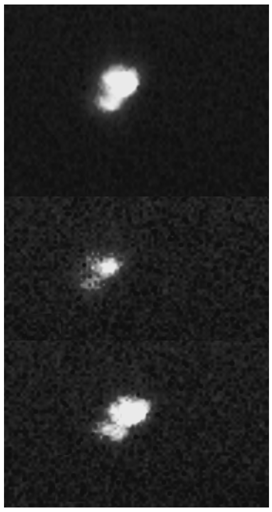
The line width, i.e., the filter pass bandwidth, was FWHM =14Å, which corresponds to the laboratory measurements. Laboratory precision measurements of the spectral temperature coefficient for the AOF in the range –40 to +60 C° in a heat-cold chamber yielded the dependence –0.55 Å/1° C. We clearly see the forbidden nitrogen ([N II]) line to the right from Hα; there is also a hint at the nitrogen line on the left. The nebula NGC 7027 was observed near the Hα line on four different nights with a temperature difference from +26 to +15 C°. It turned out that there was a noticeable shift of the band as the ambient temperature changed: -0.6Å/1° C. The subsequently performed series of laboratory measurements of the spectral temperature coefficient for the AOF in the range – 40° to + 60° in a heat cold chamber yielded the dependence –0.55Å/1°C.



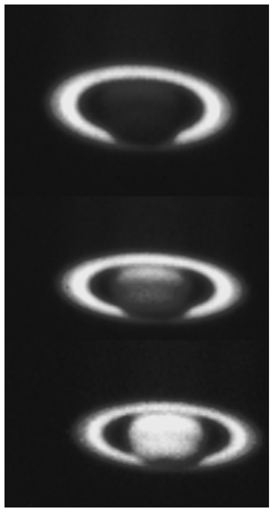


Fig.5. Planetary nebula spectral images. From top to bottom: λ 6567Å, λ 6576Å, λ 6585Å.

Fig.6. Saturn spectral. images. From top to bottom: λ 8882Å, λ 8848Å, λ 8769Å.

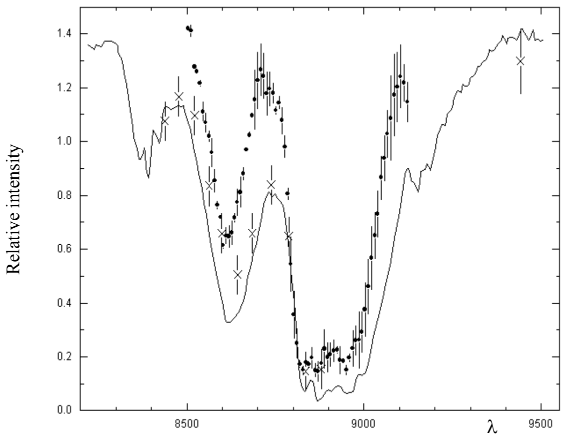


Fig.7.____Saturn's classical spectrum near the methane absorption complex from [15]; xxxxxxx AOF observations from [7], 1975; ..... AOF observations from [13], 2001

In Fig.5 the planetary nebula NGC 7027 spectral images obtained with 9Å steps at wavelengths 6567Å, 6576Å and 6585Å are shown. The acousto-optical spectrometer demonstrates high spatial and high spectral resolution. The alterations of the object's form are clearly seen in details.

Saturn's observations in the methane absorption band show the potentialities of the acousto-optical imaging spectrophotometer itself. As an example, Fig.6 shows Saturn's images obtained with the AOF at λ 8769Å and in the methane λ 8848Å and λ 8882Å absorption band. We can note the fairly high image quality provided by the filter. Saturn's ring shines by the reflected light from the Sun and its brightness depends little on wavelength. The atmosphere of the giant planet consists mainly of methane and Saturn's brightness in the methane absorption band decreases by almost an order of magnitude. The observations of Saturn were carried out on September 15. We took 73 frames with an exposure time of 10 s in the wavelength range 8500–9120Å at 10Å steps. The results are shown in Fig.7. The observations by authors [7] and Saturn's spectrum, obtained in 1973 [15] are also shown for comparison. The calibration was performed using the minimum of the main 8800 - 9000Å absorption band. Since all (not only our) measurements were made relative to the ring, they can be compared. Note that the blue edge of the third (deepest) band matches both the spectrum and the measurements by [7]. However the red edge differs markedly so the band proves to be narrower (approximately by 50Å). The second band (λ 600Å) proved to be even narrower although its blue edge, according to our measurements, matches the data obtained in [7]. It may be argued that at least the bandwidth varies with time, with the variability being most likely long-term one.

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