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SCORPIO ON THE 6 M TELESCOPE: CURRENT STATE AND PERSPECTIVES FOR SPECTROSCOPY OF GALACTIC AND EXTRAGALACTIC OBJECTS

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Abstract. A significant part of observations at the Russian 6 m telescope is carried out using the SCORPIO multi-mode focal reducer. During the past ten years, a lot of scientific data have been collected using observations in the direct imaging, slit spectroscopy and Fabry-Pérot interferometry modes. Some results of these observations are considered in this review. We also present a short description of a new generation instrument named SCORPIO-2.

Key words: instrumentation: spectrograph – instrumentation: polarimeters – ISM: kinematics and dynamics – galaxies: active

1. INTRODUCTION

In the middle of the past century Georg Courtés (1960) suggested and realized the idea of a focal reducer. In addition to the increase the field-of-view of a large optical telescope and the correction of the off-axis primary mirror aberration, a focal reducer allows to have a multi-mode instrument, since it becomes possible to install dispersing elements in the output pupil between the collimator and the camera, which turns the direct imaging system into a universal spectrograph. The first prototype of the device designed for spectroscopy and photometry of faint extended objects was an EFOSC camera at the 3.6 m ESO telescope (Buzzoni et al. 1984). Now a lot of multi-mode low-resolution spectrographs are used on middle-size and large telescopes. The SCORPIO (Spectral Camera with Optical Reducer for Photometric and Interferometric Observations) has been operated at the primary focus of the 6 m SAO RAS telescopes since September 2000. In the paper by Afanasiev & Moiseev (2005) we gave a short description of the device, while the technical details are discussed in Afanasiev et al. (2005). See also the current information presented on the SCORPIO web-page (see the footnote below). Today it is the most frequently used facility that has employed half of the observation time on the 6 m telescope (Figure 1). In this review we consider briefly some scientific results obtained with the use of SCORPIO and also our current work to modify and improve the technique for faint object spectroscopy by the SAO RAS telescope.

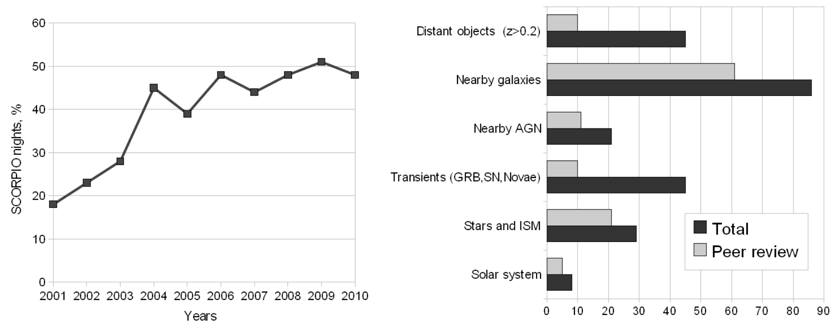

Fig. 1. The percentage of the calendar time distributed by the 6 m telescope Program Committee for the SCORPIO observations (left). Distribution of publications based on SCORPIO observations in 2001–2011 among different topics (right): the total amount (black) and peer-review journals only (gray).

2. SCORPIO OBSERVING MODES

The multi-mode focal reducer allows various spectroscopic and photometric observations to be performed within the 6 arcmin field-of-view (see, Figure 2). The list of observing modes is as follows.

- Direct imaging in broad-band $UBVR_CI_C$ filters; medium- and narrow-band interference filters.
- Long-slit spectroscopy with volume phase holographic gratings (VPHGs).
- Slitless spectroscopy for the observations of spectrophotometric standard stars.
- Multi-slit unit for spectroscopy with 16 movable slits ($18''$ in each height).
- Spectropolarimetry using the analyzer based on a Savart plate (see Afanasiev & Moiseev 2005 for the details of data analysis).
- 3D spectroscopy with a scanning Fabry-Pérot interferometer (FPI). The realization of this technique in the SCORPIO as well as the data reduction are described in Moiseev et al. (2002) and in Moiseev & Egorov (2008).

We can change the modes during the same night of observation, however, some restrictions exist. For instance, it is impossible to switch between the long-slit and multi-slit modes. Quick switching between the main modes (long-slit/imaging, FPI/imaging, etc.) allows an observer to choose targets that match best the current atmospheric conditions (i.e., seeing and transparency). That is very important in case of unstable weather at the 6 m telescope site.

3. SCIENTIFIC RESULTS

According to the SAO/NASA ADS database for the 2001 to 2011 June period, the data obtained with the SCORPIO were presented in 215 publications, including peer-review articles, conference proceedings, telegrams, etc.[1]. They have been cited more than 1000 times. Results of these observations were used in more than fifteen Ph.D. theses. Figure 1 (right) shows the distribution of these publi-

[1] The updated list of publications is available at the SCORPIO web-page: http://www.sao.ru/hq/lsfvo/devices/scorpio/scorpio.html

cations with different astrophysical topics, which reflects the main interest of the astronomers who requested observing time with the SCORPIO. It is quite impossible in a short paper to give a full review of all published results. Therefore, we will consider only certain papers selected according to our preferences in order to show a large range of tasks and methods.

3.1. Solar system

The activity of a number of distant comets was investigated using the photometric and spectroscopic observations with the SCORPIO – see, for instance, Korsun et al. (2008, 2010). The origin of the activity at distances larger than 5 AU is a puzzle, however, molecular emissions were found in some objects. For example, in C/2002 VQ94 (LINEAR) emission bands of CO^+ and N_2^+ were detected at a record heliocentric distance of 7.3 AU. This indicates that they had been formed in the outer regions of the Solar system or in a pre-solar interstellar cloud in a low-temperature ($T < 25$ K) environment.

An interesting result was obtained by Afanasiev et al. (2007), who recorded the spectrum of a faint meteor during spectral observations of galaxies with the multi-slit unit. The velocity of the entry of the meteor body into the Earth's atmosphere estimated from the emission line line-of-sight velocity is about 300 km/s. Based on these results the authors supposed that this meteor particle was likely to be of extragalactic origin.

3.2. Stars and interstellar medium

Thanks to high transparence of the optics and a large diameter of the telescope mirror, SCORPIO is widely used for snapshot and monitoring observations of faint transient objects in the framework of several programs with the aims to study the spectral evolution of novae (e.g., see Fabrika et al. 2009) and supernovae, including distant core-collapse SNe probably associated with gamma-ray bursts (Moskivitin et al. 2010). The SCORPIO data provide a spectral confirmation for newly discovered massive evolved stars (WR, LBV) in our Galaxy (Gvaramadze et al. 2009) and other nearby galaxies: M33 (Valeev et al. 2009) and DDO68. In the latter case Pustilnik et al. (2008) have discovered a luminous blue variable from the transient event in the spectra of H II region of DDO68.

Observations with a scanning FPI make possible studies of the structure of the specific spectral lines (Hα, [O III], [S II]) in a large (6 arcmin) field-of-view. It provides rich opportunities for the investigation of the emission-line kinematics of the ionized gas in interplay between stars and the surrounding medium. Examples in our Galaxy are the study of jets and emission knots ejected from young stellar objects (Movsessian et al. 2007, 2009), kinematics of bow shock fronts in the pulsar-wind nebula CTB 80 (Lozinskaya et al. 2005), and supersonic motions of the optical filament in the radio nebula W50 around the microquasar SS 433 (Abolmasov et al. 2010). The related object, a nebular complex associated with the ultraluminous X-ray sources in the dwarf galaxy HoIX, was also studied with the SCORPIO/FPI (Abolmasov & Moiseev 2008). Based on the SCORPIO long-slit and FPI data, Lozinskaya & Moiseev (2007) have presented evidences that the explosion of a very massive star (hypernova) seems to be most plausible mechanism for formation of the synchrotron superbubble in the IC 10 galaxy, compared with the earlier proposed model of multiple supernova explosions. This work is a part of a series of papers aimed at investigating the kinematics of shells and bubbles

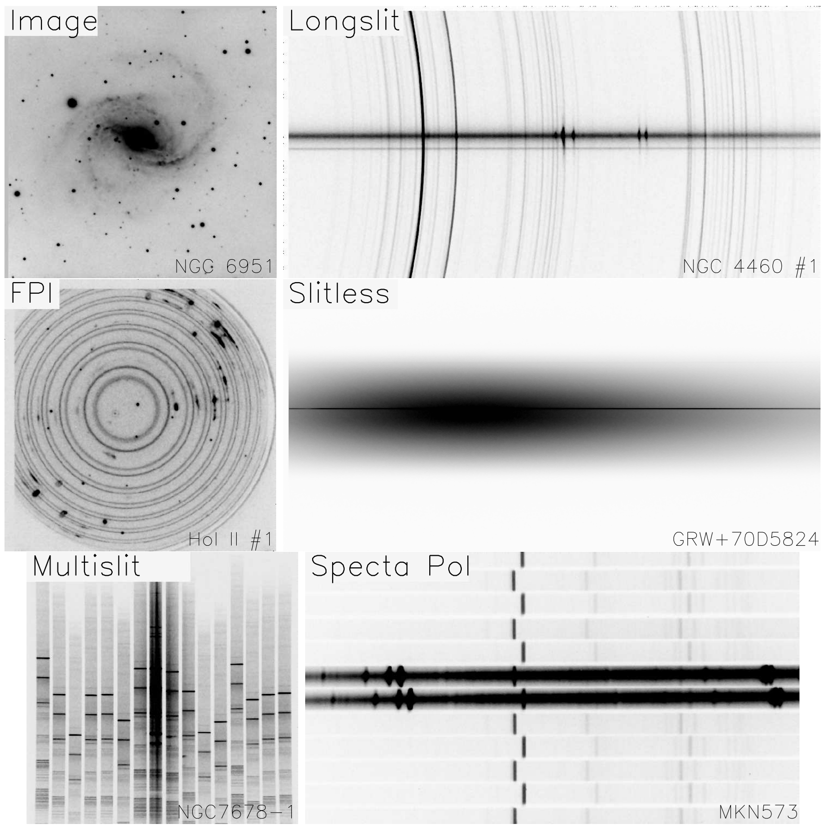

Fig. 2. Examples of the data frames for different SCORPIO modes

around star forming regions in the nearby dwarf galaxies. A good illustration is the IC 1613 galaxy, where Lozinskaya et al. (2003) have estimated the expansion velocities of multiple gaseous shells using spatially-resolved kinematic data for ionized (Hα, SCORPIO/FPI) and neutral (21 cm, VLA) interstellar medium.

3.3. Nearby galaxies

Figure 1 shows that most of SCORPIO publications are related to nearby galaxies. The Hα images for a significant part of all galaxies in the Local volume (within 10 Mpc) were obtained during a general imaging survey with the SCORPIO. Measured Hα fluxes were used to derive the total star formation rate density in the Local universe – $0.019 \pm 0.003\ M_{\odot}\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$ (Karachentsev & Kaisin 2010). The SCORPIO long-slit spectra were used to study the stellar population in two dE/dSph members of the nearby M81 group of galaxies (Makarova et al. 2010), whereas Chilingarian et al. (2009) used the multi-slit unit for follow-up spectroscopy of newly discovered compact elliptical galaxies in order to investigate their origin and stellar population properties.

We have discussed already the ionized gas properties in the nearby dwarf galaxies. Using the SCORPIO/FPI observations, Martínez-Delgado et al. (2007) have mapped the regions of supersonic gas motions in distant blue compact galaxies. They offered kinematic diagnostic diagrams that provide a possibility to infer from the FPI data the star formation activity in the galaxies, even if they are not spatially resolved. The spectrophotometric observations with SCORPIO allow one to estimate the oxygen abundance in H II regions of extremely metal-deficient galaxies (see Pustilnik et al. 2010 and references therein). A detailed analysis of the ionized gas morphology and kinematics in nine such galaxies shows an important role of recent interactions and mergers in triggering their star formation activity (Moiseev et al. 2010).

The ionized gas velocity fields derived from the SCORPIO/FPI data cubes reveal a complex kinematic picture in the disks of spiral galaxies caused by internal (secular evolution) and external (merging, gas accretion) effects: inflow steaming motions in bars, polar disks and rings, circumnuclear counter-rotating components (see previous review in Moiseev 2007). The FPI kinematic mapping is very helpful in the study of structure and dynamics of peculiar galaxies: colliding ring and polar ring galaxies (see references in the review by Moiseev & Bizyaev 2009). Polar rings are an interesting example of peculiar systems that reveal outer rings or discs, rotating in the plane approximately perpendicular to the disk of the main galaxy. The recent progress in the study of polar rings with SCORPIO was presented by Brosch et al. (2010) who found the most distant kinematically confirmed polar ring ($z = 0.06$). Here an early-type central galaxy is surrounded by a giant (with a diameter of over 48 kpc) ring of young stars and clouds of the ionized gas, inclined at a steep angle to the stellar disc. In contrast to this large-scale structures, Moiseev (2010) has described the smallest ($r < 2$ kpc) polar gaseous disks in blue compact dwarf galaxies. The possible formation mechanisms for these disks are the merging or accretion of external gas clouds with a specific direction of the orbital momentum. It was also suggested by Sil'chenko et al. (2011), who studied the stellar population and kinematics properties in the NGC 7217 early-type galaxy using the SCORPIO long-slit data. A minor merging event is also the most likely reason for the origin of full-size gaseous disks rotating in the opposite direction to the stellar disks in the NGC 2551 and NGC 5631 lenticular galaxies (Sil'chenko et al. 2009).

The SCORPIO advantages in the spectroscopy of regions with low surface brightness can be illustrated by the papers of Zasov et al. (2008) on stellar kinematics of the disks in S0-Sa galaxies and by Baes et al. (2007), where the stellar population age and metallicity distributions in a sample of elliptical galaxies are estimated up to distances of 3 effective radii. The main conclusion of this work is the absence of a single power law for the metallicity gradient, what is inconsistent with the origin of elliptical galaxies by a major merger.

3.4. Nearby AGN

Together with the data obtained with other instruments, the SCORPIO spectra were involved in the long-term monitoring of Hα and Hβ line variations of the active nuclei of NGC 4151 (Shapovalova et al. 2008) and 3C390.3 (Popović et al. 2011). The main aim was a study of their 'central engines' including the Broad Line Region (BLR). The geometry of the BLR of 3C390.3 seems to be very complex, with the possible presence of inflows/outflows, but the disk-like BLR seems to be the dominant emitter.

Recently, Afanasiev et al. (2011) presented the results of spectropolarimetric observations for a sample of 15 active galactic nuclei. The magnetic field strengths and radial distributions in the accretion disks around supermassive black holes were evaluated within the framework of traditional accretion disk models.

Large-scale environments of the active nuclei were also investigated in numerous papers based on the data collected in the FPI mode. Smirnova et al. (2007) presented the analysis of the global ionized gas kinematics in the disk of Mrk 533. In this galaxy, non-circular ionized gas motions at a distance of $r < 2.5$ kpc are associated with an outflow triggered by the nuclear radio jet intrusion in an ambient medium. A very complicated combination of the region with different ionization and kinematical properties was found in Mrk 344 (Smirnova & Moiseev 2010). The most unusual feature is a large-scale cavern filled with a low-density ionized gas. This region seems to be the place where remnants of a disrupted companion have recently penetrated through the gaseous disk of the main galaxy.

3.5. Distant objects

SCORPIO shows a good advantage in the spectral identification of the extragalactic radio sources in a wide range of optical magnitudes up to $m_r = 23$–24 mag; e.g., see the classifications, optical identifications and spectral redshifts for different samples of radio sources presented by Amirkhanyan et al. (2004) and Afanasiev et al. (2003). Some interesting objects were discovered. For example, Amirkhanyan & Mikhailov (2006) found a very radio-loud QSO at $z = 4.06$. Recently Parijskij et al. (2010) presented the results of spectroscopy of 71 radio galaxies and QSOs with steep and ultra-steep spectra.

SCORPIO follow-up spectroscopy makes a significant contribution to the systematic searches for wide separation gravitational lens systems in the framework of CAmbridge Sloan Survey Of Wide ARcs in the skY (CASSOWARY). The most beautiful object (in our view) was the discovery of the Cosmic Horseshoe (CASSOWARY #1) an almost complete Einstein ring of the diameter of $10''$ around a giant luminous red galaxy at $z = 0.444$ (Belokurov et al. 2007). The source is a star-forming galaxy with $z = 2.379$. This gravlens has a large magnification factor $(25 - 35)$ which allowed Quider et al. (2009) to study from VLT spectroscopy the metallicity and star formation properties in the source galaxies with the quality that is currently unfeasible for unlensed galaxies at $z \sim 2 - 3$.

4. NEW PERSPECTIVIES

During its ten years of operation, SCORPIO has been repeatedly upgraded and improved. Unfortunately, opportunities for further upgrading have been exhausted. Also, a new optical scheme was necessary for spectral observations with a large format CCD detector. Therefore SAO RAS began manufacturing a new multi-mode spectrograph with enhanced capabilities. The main novelty of SCORPIO-2 versus its previous version are as follows (see also Table 1):

- The value of off-axis optical aberration is significantly (by half) decreased.
- The device is especially designed to work under remote control from the Institute building (under the mountain where the telescope is sited). The number of changable elements installed simultaneously in the device is significantly increased.
- The opportunities for polarimetry (spectra and images) are greatly expanded.
- The new multi-mode focal reducer includes an integral-field unit (IFU) based

Table 1. Comparision of the old and new SCORPIO focal reducers.

	SCORPIO	SCOPIO-2
Detector	EEV 42-40, 2K $\times$ 2K	E2V 42-90, 2K $\times$ 4.6K
Direct imaging: Max. filter positions Field-of-view	 10 (in two wheels) $6.1'$	 27 (in three wheels) $6.1'$
Long-slit spectroscopy	Set of slits with a fixed width (0.5–$2''$); a single WPHG position	Variable slit width (0–$20''$); wheel with 9 grating holders
FPI	Common carriage with grating holder	Independent holder
Multi-slit unit	16 slits in $6' \times 3'$field-of-view	16 slits in $6' \times 4'$ field-of-view
Integral-field unit		24×24 lenslet, $0.75''$ per lens
Polarimetry	Savart plates, rotated in two positions	Single and double Wallaston prisms; apochromatic phase plates $\lambda/2$, $\lambda/4$; rotated analyzer

on the combination of small lenses with optical fibers. This layout was offered by Georg Courtés (1982), and it was first implemented in the two generations of the Multi Pupil Fiber Spectrographs (MPFS) at the 6 m telescope (Afanasiev et al. 1990, 2001). Now this type of IFUs is widely used in the middle- and large-size telescopes. The SCORPIO-2/IFU with a $18'' \times 18''$ field-of-view is divided by a square lens array with a scale of $0.75''$ per lens. Behind each lens an optical fibre is located, the other end of which is packed into two pseudo-slits in the spectrograph entrance.

The first test observations on the 6 m telescope were carried out in June of 2010. Some electronic and mechanical parts (integral-field and multi-slit units) are still under construction. We are confident that the commissioning of SCORPIO-2 will significantly enhance the abilities of the 6 m telescope in the study of different Galactic and extragalactic objects.

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