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TO THE 30th ANNIVERSARY OF THE SPECIAL ASTROPHYSICAL OBSERVATORY

Below we present two reports delivered at the Conference dedicated to the 30th anniversary of the Special Astrophysical Observatory which was held in the fall 1996

Spectral monitoring of active galactic nuclei

N. G. Bochkarev[a], **A. I. Shapovalova**[b]

[a] Sternberg Astronomical Institute of Moscow State University, Universitetskij Prospect 13, 119899, Moscow
[b] Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 357147, Russia

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Abstract. This paper is a presentation of history of ground-based optical monitoring of active galactic nuclei (AGN) of the Seyfert galaxies NGC 3516, NGC 4151, NGC 5548, NGC 7469 and 3C 390.3 at the 6 m telescope of the SAO RAS. Theoretical foundations of investigation into the structure and kinematics of the "central engine" of AGN are briefly discussed, principal results of the 6 m telescope observational programme carried out in 1983–1996 are presented. The 6 m telescope observations in the years 1983–1995 were performed with the TV scanner at the wavelengths between 4000 Å and 5200 Å with a signal-to-noise ratio of about 20. 500 spectra were taken. A CCD camera and two- and three-dimensional spectrographs were used to take practically all the spectra (270) in 1996 at the wavelengths from 4000 Å to 7000 Å. The Seyfert galaxies NGC 5548, NGC 7469 and 3C 390.3 were observed in the optical range at about 40 ground-based observatories and also with the satellites IUE and HST in the ultraviolet range within the frames of the international programme "AGN Watch". The immediate prospects of the work on the programme of optical monitoring of AGN with the use of the SAO RAS facilities and potentialities of the observatories "Spectrum-X-Gamma" and "Spectrum-UV" to be launched are considered.

Key words: galaxies: active – galaxies: Seyfert – galaxies: structure

1. Introduction

1.1. Historical remarks

One of the authors (N. Bochkarev) who was lucky to carry out a programme of spectral monitoring of active galactic nuclei (AGN) had had an opportunity to stay at the SAO in August 1973, before the first mirror was installed in the BTA. At that time he was a post-graduate student of S. B. Pikel'ner and concerned with purely theoretical problems: calculated the response of interstellar gas to variations of the X-ray radiation flux which ionizes this gas. For a short while he lived together with S. B. Pikel'ner in Zelenchukskaya, and then lived for about a month sheltered in the BTA dome, and used for calculation a computer M222. One could hardly beleive at that time that these computations would underlie a BTA observing programme of many years.

1.2. Theoretical foundation of the programme

Active galactic nuclei are being studied now by many researchers all over the world. The basic problem in the study of AGN has been the investigation into the "central engine", which is a source of very powerful energy release. Unfortunately, direct methods fail to examine the structure of this machine. Energy release occurs chiefly in the regions of formation of broad emission lines (BLR). They are of the order of 10^{17} cm in size, most of the energy being liberated in the innermost regions of BLR. But the size of BLR corresponds to about 0.001 arcsec even for the nearest objects. The desired angular resolution can presently be attained only by the techniques of radiointerferometry, however in the majority of AGN the "central engine" is surrounded by a great amount of gas smearing the radio image. For this reason, only indirect methods are applicable to the study of energy releasing regions in AGN. In the immediate vicinity of a supermassive black hole supposed to exist at the centre of AGN, the gas is heated to a high temperature and emits in the X-ray range. The X-ray radiation from AGN is variable: rapid flares (at times of minutes–days) with several-fold flux variations are observed. The rapid variation in the flux of ionizing radiation results in an ionization wave running across BLR and the filling factors of gas emission in spectral lines change. For an observer at infinity, the isochrones have the shape of a paraboloid of rotation with a common focus in the place of location of the X-ray radiation (Fig. 1). If gas in BLR has a systematic motion: infall, expansion, circular motion etc., then variations in profiles of broad spectral lines dependent on the geometry and kinematics of gas in BLR, as well as on the process of relaxation of gas following the ionizing radiation flux variations, must be observed. It is the latter that was the subject of the above-mentioned investigation described by Bochkarev and Pudenko (1975). In 1980 Bochkarev initiated numerical modelling of the response of profiles of broad emission lines produced in media with different geometry and kinematics of gas to the jumping variations of the X-ray flux from the nucleus. The qualitative picture is described in the "pioneer" paper by Fabrika (1980). Despite the delay in publication, our quantitative analysis (Bochkarev and Antokhin, 1982; Antokhin and Bochkarev, 1983; Fig. 2) was published simultaneously with the famous paper by Blandford and McKee (1982), in which a lame, but quite a widespread, name was proposed to the method of analysis of the BLR structure ("echo mapping") from the response of the line profile to the fast variations of the X-ray flux from AGN (a better term, "reverberation mapping" has lately been adapted, see Peterson, 1993). From these publications quantitative predictions followed: AGN with small amount of gas and moderate frequency of X-ray flares (of type Sy 1.5) for which one may expect variations of 3–10% at times of 1–3 days in individual parts of broad emission line profiles, are the most suitable for the study of the structure and kinematics of BLR. The amplitude of the response and the wavelength range in which profile variations may be expected increase with growing interval of time between the X-ray flares and the moment of observations up to 0.5–1 month (for details see Bochkarev, 1987a). However, with larger intervals between observations the results obtained carry less information.

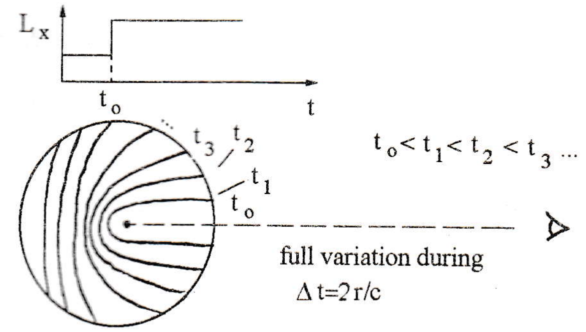

Figure 1: *Isochrones of the event occurring in a point source for the observer at infinity. At the top is shown a jump of ionizing radiation flux from the central source. Below are lines (surfaces) from which the signal of the event that has occurred in the central source reaches the observer at infinity (shown at the right) simultaneously.*

2. AGN spectral monitoring programme

2.1. Beginning of the observational programme

Immediately after the publication of quantitative predictions, N. Bochkarev made attempts to obtain observational data. The BTA scanner was the only facility for the desired observations in our country. The 6 m Telescope Programme Committee headed by academician V. V. Sobolev at that time supported the proposal for observation. With many appreciative thanks we go back in our thoughts to detailed discussions of the programme (proposed by a young theorist) with I. M. Kopylov, help on the work of O. I. Spiridonova and engineers of the SAO, when N. G. Bochkarev came to the observatory for his first observations in the spring of 1983. In the observations of March and May–June 1983 he obtained reliable estimates of H_β line profile variations in the nucleus of the Seyfert galaxy NGC 4151 during two months (Fig. 3; Bochkarev, 1984), which was of importance at that time: by that time, most of the similar variations had been recorded only in spectra taken with an image tube, i.e. with a very low signal-to-noise ratio. Variations on time scales from 1 to 3 days were lost in the noises of measurements.

After the BTA TV spectrum scanner was updated (the dynamical range was widened and the number of channels doubled) the observations were resumed, and have so far been continued since the spring of 1986 (thanks to A. I. Shapovalova).

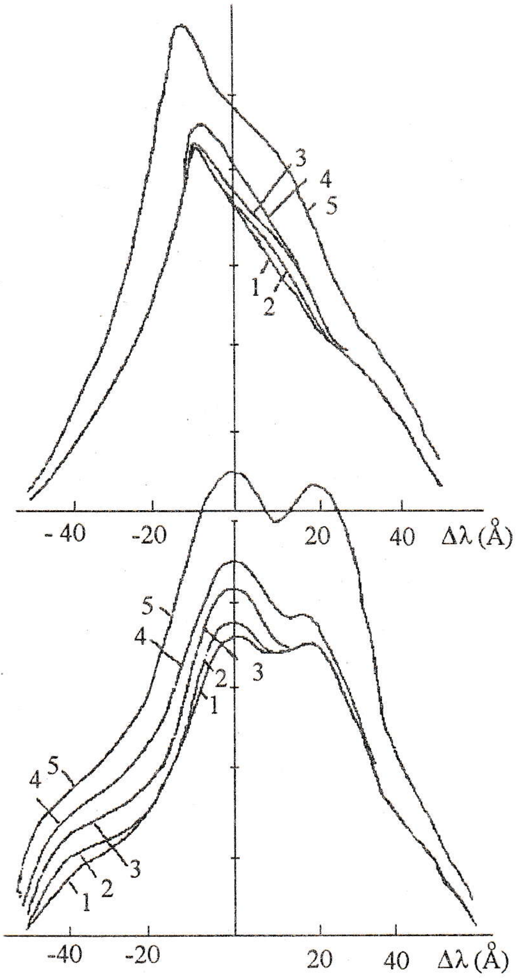

Figure 2: *Expected variations of the emission profile of the broad component of the hydrogen spectral line* H_β *after the 2-fold momentary increase in the X-ray flux from the central source for two models of BLR: infalling of gas with acceleration in the disk (top) and uniform spherical expansion of gas (bottom) (Bochkarev and Antokhin, 1982; Antokhin and Bochkarev, 1983). The numbers by the curves indicate the shape of the profile at sequential moments of time: 1 – initial profile; 2 – 8 hours after the jump of the X-ray flux; 3, 4, 5 – 32 hours, 80 hours and 37 days after the jump, respectively, when the emission profile reaches a new steady state.*

2.2. Characteristics of the programme

The observing programme has been carried out (especially for the last few years) as a background programme, i.e. under the conditions unsuitable to accomplish the main programmes: generally a seeing no better than 3 arcsec, cloud amount 30–80 percent, light sky (period around full moon). Untill late 1994 the spectrograph SP-124 placed at Nasmyth 1 focus with the TV scanner was employed. During the last two years (1995-1996) observations with CCD detectors have been performed.

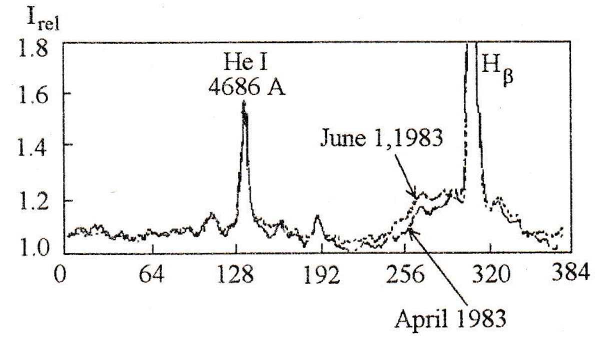

Figure 3: *Intensity variations of the short-wavelength wing of* H_β *in the period from April to June 1, 1983, which were observed with the BTA TV scanner (Bochkarev, 1984). The horizontal axis is the number of scanner channel, the vertical axis is the radiation intensity normalized to the continuous spectrum.* H_β *line (right), HeII 4686 Å (left).*

Apart from the authors of the report the following people took part in carrying out the programme: post-graduate S. A. Zhekov (1987–1988), visiting astronomer L. S. Nazarova (1991), SAO researchers A. N. Burenkov, V. V. Vlasyuk, V. P. Mikhailov, I. P. Kostyuk and others. In the 1980s much attention to the programme was given by V. A. Lipovetsky. Over the last few years the programme has closely been attended by V. L. Afanasiev and S. N. Dodonov.

Among other major long-term BTA programmes, the programme of monitoring AGN looks less time-consuming. Over the decade 30 observing nights have been alloted for the programme (10–20 times less than for the other programmes discussed at the conference), about 250 hours of observing time were actually used (including the time spent for pointing the telescope) over 600 spectra of AGN have been taken for NGC 4151, NGC 3516, NGC 7469, 3C 390.3.

2.3. Development of the techniques

In March and early April of 1986 18 spectra were taken (Fig. 4) of the NGC 4151 nucleus in the range 4000 to 4900 Å (without the lines [OIII] 4959 Å and 5007 Å, which, because of their intensity, were in the non-linear mode of scanner operation). However, using the scanner, it was impossible to obtain a signal-to-noise ratio better than 10–25 in the continuum and in the wings of broad emission lines. This ratio is insufficient for echo mapping. This is why spectra averaged over several nights (3 upper spectra in Fig. 4) or over the whole observing run (lower spectrum in Fig. 4) were analysed. In the latter case, the

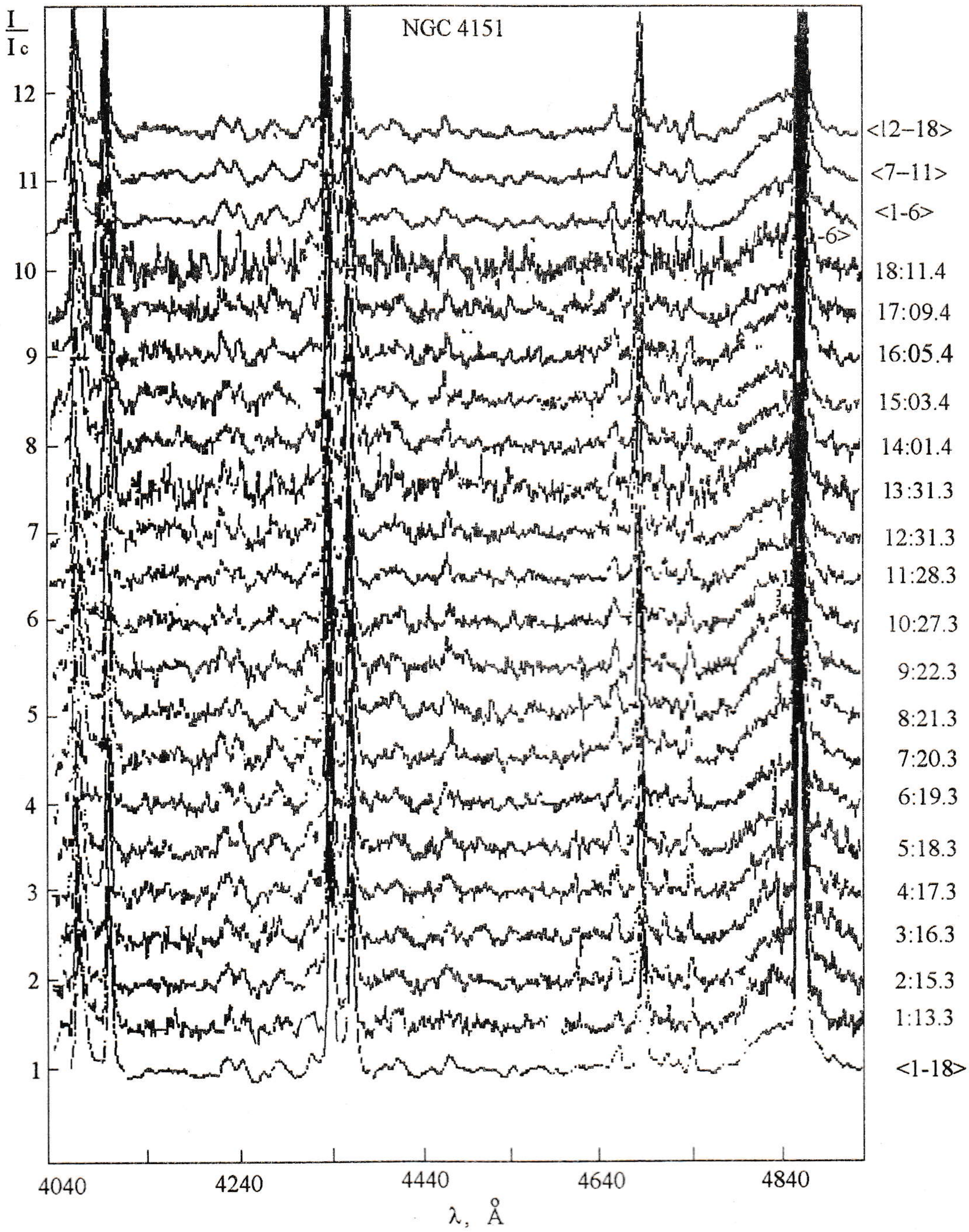

Figure 4: *Active galactic nucleus spectra of NGC4151 obtained with the BTA between March 13 and April 11, 1986 and normalized to the continuous spectrum (Bochkarev, Shapovalova and Zhekov, 1989a, 1991). On the right are indicated the ordinal numbers of the spectra and the dates of observations. Three spectra averaged over 5–7 dates are shown at the top. The spectra below them are the mean over all 18 dates. The wavelengths are corrected for the AGN motion with respect to the observer.*

S/N reached 50 with losing information on variability.

In 1986–1988, collection of data, development of the technique of measurements and their reduction were carried out. In observations of spectral variability of extended sources (such as galaxies) it is easy to obtain a seeming variability but it is difficult to prove that it is associated with the true variations in AGN. There were phenomena which later turned out to be artifacts. The powerful peak that appeared at 4508 Å at the level of 8 standard deviations on 26.02.88 (Bochkarev et al., 1988) proved to be a speck of light in the spectrograph. When observing with different seeing, different amounts of light from the bulge is added to the radiation from the nucleus. In Fig. 5 is shown the spectrum of the NGC 3516 nucleus observed in 1988 (middle line), the spectrum corresponding to the bulge radiation (lower line) and the difference between them (upper line). It is clearly seen that the correction of observations for the radiation from the bulge, whose contribution reaches 70 %, strongly changes the shape of the broad components of spectral lines (Bochkarev et al., 1989b, 1990).

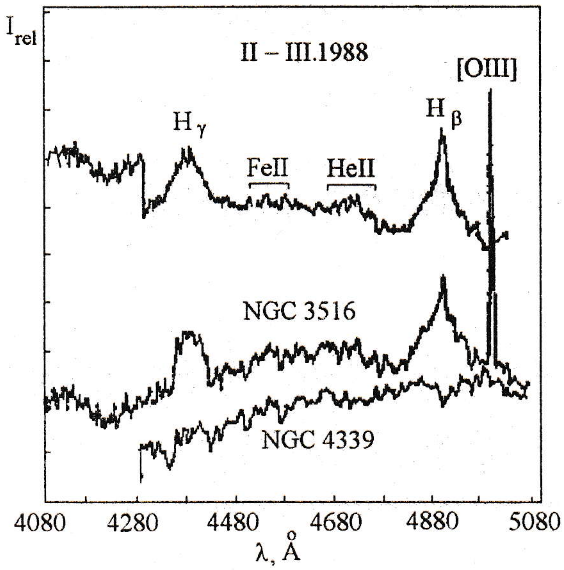

Figure 5: *The NGC 3516 spectrum averaged over the BTA observations in 1988 is shown in the middle. The spectrum of an elliptical galaxy, corresponding supposedly to the radiation of the NGC 3516 bulge, is the lower one. The upper spectrum is the spectrum of the AGN corrected for the bulge radiation (Bochkarev et al., 1989b, 1990).*

2.4. First results

Analysis of average spectra allowed the long-term (months–years) variability of spectral features to be studied in detail. In 1984–1987 the nucleus of the galaxy NGC 4151 passed across a deep minimum of light. Fig. 6 shows the variations of the broad component of H_β in 1986–1996 (Shapovalova et al., 1996). From 1987 to 1995 the luminosity of the broad component increased by a factor of 8. During the decade indicated, the blue and red wings of Balmer lines varied quasisimultaneously, and the blue wing remained stronger than the red one. The wings of the broad components of the line HeII 4686 Å varied quasiperiodically: every 2 years the dominant wing of the line changed (Fig. 7; Bochkarev et al., 1992; Bochkarev et al., 1996). We also confirmed the quasiperiodic character of variations for the ratios of the observed fluxes of the blue and red wings of the H_β line in 3C 390.3 spectra. (Shapovalova et al., 1996). The detailed emission spectrum observations of the NGC 4151 nucleus during the period 1986–1988, when the object was in a deep minimum of brightness and there were very few broad emission features, permitted us, using averaged high S/N spectra, to suspect the existence of narrow satellites of Balmer lines (Fig. 8; Bochkarev et al., 1989a, 1991). They resemble the CIV 1549 Å line satellites L1 and L2 found with IUE (Ulrich et al., 1985; Clavel et al., 1987). An analysis of data on the satellites of hydrogen lines and CIV in the model of opposite jets made it possible to estimate the mass of the NGC 4151 nucleus (100–300 million solar masses) and the velocity of the jets in the region where they produce hydrogen lines (8–24 thousand km/s, depending on the angle of inclination of the jets to the observer). Later the NGC 4151 nucleus changed to the state of high luminosity, which impeded observation of the faint satellites against the bright background of the nucleus radiation. Their further study turned out to be impossible.

The spectra of AGN taken with the BTA scanner allowed us to determine or refine the parameters

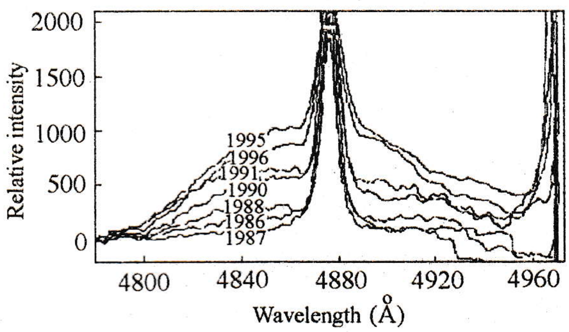

Figure 6: *Annual average H_β line profiles in the spectrum of the NGC 4151 nucleus for the years 1986 to 1996 (Shapovalova et al., 1996).*

of narrow emission lines (Bochkarev et al., 1989a, b, 1990, 1991).

2.5. Theoretical research

The work was not confined only to acquisition, reduction, primary interpretation of observations and construction of simple models. In ascertaining physical conditions in the regions of formation of spectral lines theoretical calculations were involved as well. From the joint solution of equations of radiation transfer in spectral lines of hydrogen and HeII (Bochkarev and Nazarova, 1991; Bochkarev et al.,

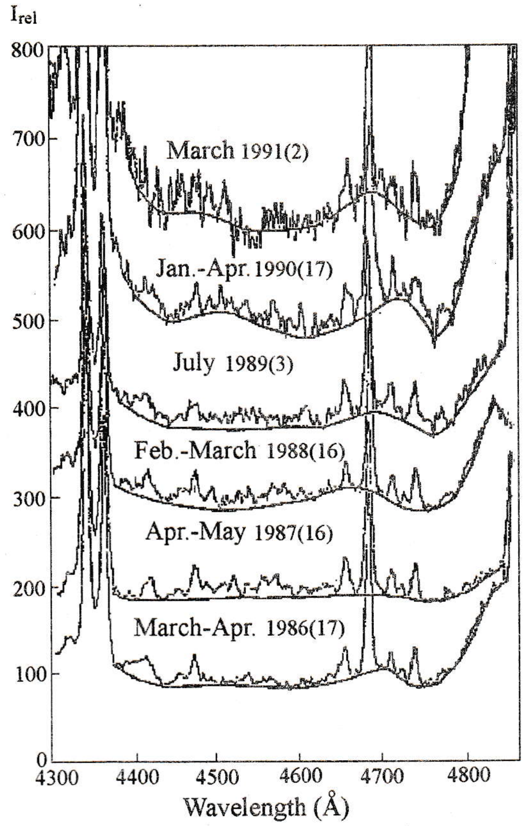

Figure 7: *Profile variations of the broad component of HeII 4686 Å in the spectrum of the NGC 4151 nucleus (Bochkarev et al., 1996). Above the spectra are indicated the time interval over which the spectra are averaged. In 1986 and 1990 the red wing of the line was stronger than the blue one, in 1988 the asymmetry of the profile was opposite. In 1987, 1989 and 1991 the asymmetry was minor.*

1992) we have established probable physical conditions in the regions where HeII lines and hydrogen lines of the Lyman series form: concentration of electrons $(10^{11} - 10^{12})\,\mathrm{cm}^{-3}$ and temperature (20000–30000) K. The Balmer lines form predominantly in cooler regions of gas together with other lines of singly charged ions of low ionization potentials (FeII and others).

2.6. International cooperation

It is obvious that one fails to obtain long series of close dense observations needed for echo mapping of AGN with the BTA. Besides, it is extremely desirable to obtain not only spectral but also photometric observations in both the optical and the ultraviolet ranges (Bochkarev, 1987a, b). For this reason, beginning with IAU Symposium 121 held at the Byurakan Observatory we had repeatedly attempted to arouse interest of our foreign colleagues in our programme.

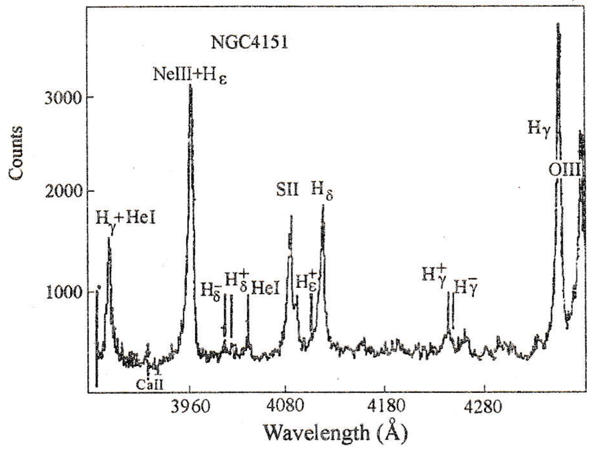

Figure 8: *The NGC 4151 spectrum averaged over 1987, when the intensity of broad components of spectral lines was minimum (Bochkarev et al., 1989a, 1991). Identification of narrow spectral lines and the position of supposedly observed narrow satellites of Balmer lines with radial velocities of −7500 km/s (marked "−") and +9400 km/s (marked "+").*

Several years later our attempts were crowned with success. However, the underdeveloped telecommunication facilities in our country, as well as other difficulties of contact with the colleagues abroad of that time, led to the fact that researchers from the USA and Europe took the lead in the international programmes of monitoring AGN. From the very beginning we have been taking active part in them.

An extensive international co-operation called "AGN Watch" was initiated in December, 1988 and involved about 100 people from approximately 50 establishments of dozens of states.

Coordination of the co-operation was taken on by B. Peterson from the USA. Apart from a number of optical telescopes distributed over the globe, which are used to perform photometric and spectral observations, it was managed to organize dense series of measurements on the ultraviolet telescope IUE and Hubble Space Telescope. The nucleus of the Seyfert galaxy NGC 5548 was chosen to be the first object to observe. Later the programme was extended to other AGN.

Four-year sequences of "AGN Watch" observations in the optical and ultraviolet ranges allowed dense series of observations to be obtained in spectral lines and in the continuum for the first time (Fig. 9 Peterson et al., 1994) and the most reliable data on the lag of the intensity variations of broad emission lines with respect to the variations in the continuum to be extracted (Fig. 10 Peterson et al., 1994). The first attempt to observe such a lag, t, and thus define the size of the region where broad emission lines form, R = ct, where c is the velocity of light,

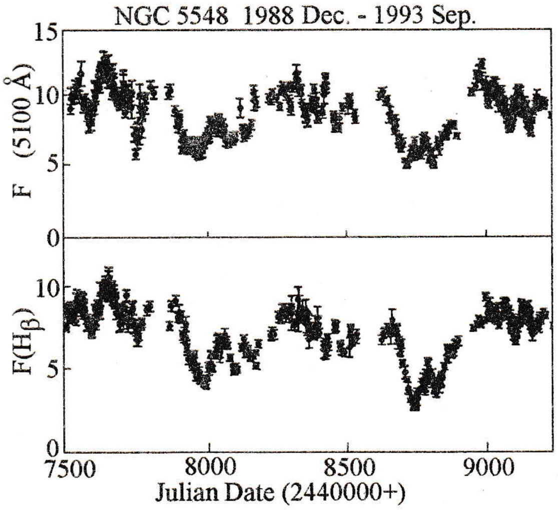

Figure 9: *Intensity variations of the continuous spectrum around 5100 Å and H_β line of the nucleus of the Seyfert galaxy NGC 5548 between December 1986 and September 1993 (Peterson et al., 1994).*

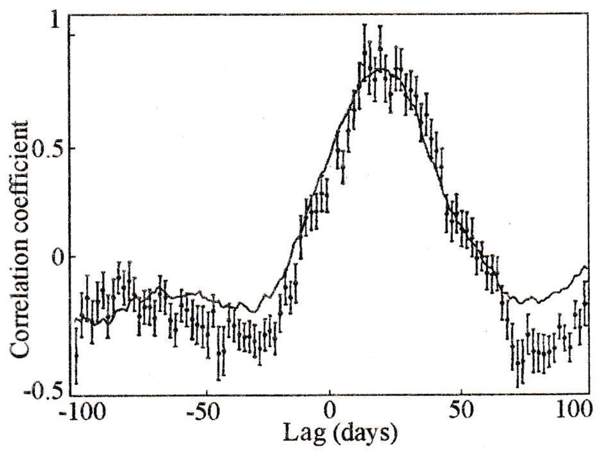

Figure 10: *The cross-correlation function of the intensity variations of the continuous spectrum and H_β line presented in Fig. 9. The H_β line intensity variations delay can be seen with respect to the continuum by approximately 20 days, which points out that the size of the H_β broad line region in NGC 5548 is about 20 light days.*

was made by Cherepashchuk and Lyuty (1973). The "AGN Watch" programme investigations (Peterson et al., 1991, 1994; Dietrich et al., 1993; Korista et al., 1995) were succesful in deriving R not only for the hydrogen line H_β but also for the lines of highly ionized ions (CIV 1549 Å). The highly charged ions were confirmed to emit predominantly closer to the source of ionizing radiation than hydrogen, the sizes of the radiating regions being different several times.

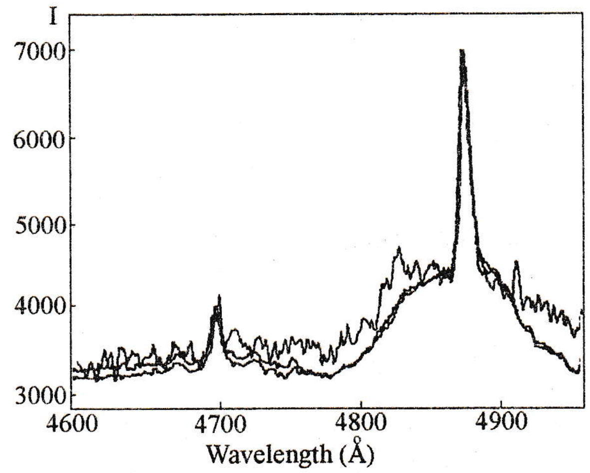

Figure 11: *A comparison of the unreduced individual spectrum of the NGC 4151 nucleus derived in 1991 with the BTA TV scanner and two spectra of the same object acquired in 1996 with a CCD detector. The signal-to-noise ratios are seen to be greatly different.*

The study of the region emitting broad emission lines of FeII (Maoz et al., 1993) was also a success.

The new generation detectors and spectral equipment of the 6 m telescope, have become accessible during the last two years (1995-1996), and the techniques for reduction of huge arrays of spectral data developed at the SAO (Vlasyuk, 1993) improved radically the quality and variety of AGN monitoring data obtained at the observatory.

CCD detectors used for spectrum recording instead of the TV scanner have increased the signal-to-noise ratio from 10–20 to 50–100 (Fig. 11). The multipupil field spectrograph MPFS (Afanasiev et al., 1990) has made it possible to measure spectra of matter surrounding AGN: stellar bulge and extended narrow emission line formation regions (Fig. 12).

3. Principal results

The principal results obtained over the decade (1986–1996) are as follows.

1. The size of BLR is twice as small as supposed previously (the volume of BLR turned out to be an order of magnitude smaller than it had been deamed earlier).
2. A BLR is stratified: the CIV and HeII ion lines are produced in a smaller volume than the hydrogen Balmer lines.
3. The behaviour of broad FeII lines is approximately the same as that of the line H_β and they form approximately in the same region of space.
4. The variations in blue and red wings of broad emission lines are practically simultaneous, which im-

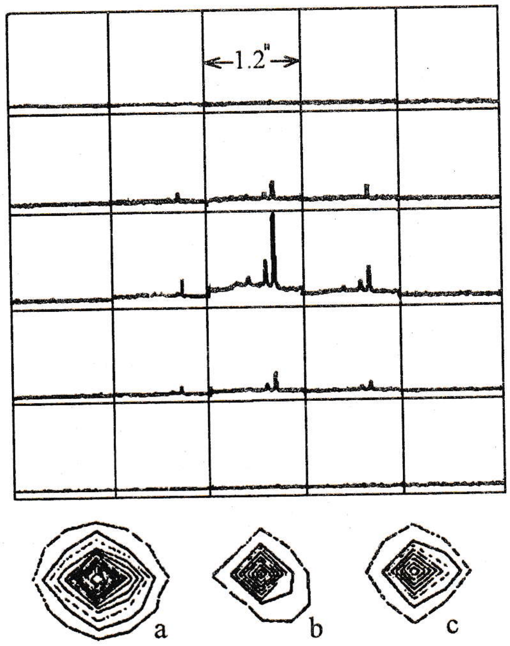

Figure 12: *The spectrum of the central part of the Seyfert radio galaxy 3C 390.3 taken at the BTA with MPFS on May 30, 1995 (Shapovalova et al., 1996). Each square contains the spectrum of a part of the galaxy* 1.2 × 1.2 *arcsec in size. Below are shown the isophotes of the nuclear region in the continuum (a) and spectral lines H_β (b) and [OIII] (c) derived from the spectrum.*

plies that circular, but not radial motions (outflow or infall of gas) are predominant in the BLR.

5. Narrow satellites of the Balmer lines have been suspected to exist in the nucleus of NGC 4151, which provides information on the region of formation of the jets.

6. New data on the regions of formation of narrow emission lines have been obtained: widths and radial velocity shifts of one lines with respect to others have been estimated (NGC 4151, 3516); an intermediate (in width) component of the [OIII] 5007 Å emission line with a velocity dispersion of 2000 km/s has been revealed and the sizes of the regions of formation of particular narrow emission lines (3C 390.3) have been found.

4. Prospects

The renaissance of the BTA light detectors and placing in service of well-fitted minor telescopes on the BTA site is an impetus to further development of the AGN monitoring programme at the SAO. CCD spectra with a S/N of 100 enable the variations of the broad emission line profiles, which have been predicted by the computations of Bochkarev and Antokhin (1982), Antokhin and Bochkarev (1983), to be measured at a level of 2–5 %. Two-dimensional (long slit) and three-dimensional (MPFS) spectroscopy permits reliable reduction of spectra, separating the radiation of the AGN itself from the contribution of the bulge and gas surrounding the nucleus. It has become possible now to correct spectra for the bulge radiation of the host galaxy, without involving another galaxy having supposedly a similar spectrum of the bulge. Check of the admixture of the radiation of gas surrounding the AGN makes it possible to keep out the seeming profile variations of broad emission lines caused by the variation of the contribution of the AGN environment to its spectrum with varying seeing.

The employment of the minor telescopes with CCD detectors located beside the 6 m telescope makes it possible to transfer part of the observations to the 1 m telescope, which can increase the frequency of spectral observations and make it approach the ideal condition of 2–3-days' acquisition, and to obtain broad-band photometric observations of AGN quasisimultaneous with spectroscopy (60 cm telescope), i.e. to make measurements not only in spectral lines but also in the continuum, which is necessary to attain the aim of the AGN monitoring programme. Moreover, the homogeneous series of observations with the devices of the same kind permit the errors inevitably appearing because of intercalibration of data obtained on many telescopes with various devices under extremely different observing conditions to be avoided.

Multifrequency radio observations of AGN with large enough radio fluxes (for instance, 3C 390.3, NGC 4151) with the RATAN-600 correlated with optical observations can make it possible to obtain data on the lag of radio radiation variations at different frequencies with respect to optical continuum and spectral line variations and provide new material on the structure of the central regions of AGN.

Besides, for accumulation of photometry data it is presumed to involve observations obtained at other observatories of the former USSR. For theoretical comprehension of results, we contemplate to use the algorithms of numerical modelling of gas radiation under the conditions characteristic of AGN, which are well developed by the world community.

5. Next steps

As long-range perspective, one should mention brilliant prospects of development of the monitoring programme in connection with the launch of space observatories "Spectrum — X-rays — Gamma" in the late 1990s and then "Spectrum — UV". A co-operation with X-ray observation will offer strong possibilities in obtaining direct data on the ionizing flux variations which cause the spectral line profile variations. Co-operative (with "Spectrum — UV") observations may widen the scope for acquisition of data on the radiation variations of bright AGN in the ultraviolet range.

To make the ground-space AGN monitoring highly efficient, it is needed to attain a higher level of coordination of observational programmes of the 6 m telescope and space-borne observatories than it was possible in the USSR. However the launch of the space instruments should be met in "full possession of arms", i.e. first of all, the technique of complex optical observations must be perfected, taking into account the above-mentioned new possibilities already available.

6. Conclusions

So, the present-day astrophysics is on the threshold of new vast prospect in solving of one of the major problems — revealing the structure of the "central engine" of active galactic nuclei by the technique of complex monitoring of their radiation in different spectral ranges. The unique situation of the nearest decade favours a great contribution to be made to the solution of the problem on the part of Russia. The most important role in its solution is to be played by the SAO.

Our duty is to realize to the highest degree the novel possibilities to obtain new results.

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