Publ. Astron. Obs. Belgrade No. 66 (1999), 55 – 64

SPECTRAL LINE INVESTIGATION OF ACTIVE GALACTIC NUCLEI AT BELGRADE OBSERVATORY

LUKA Č. POPOVIĆ
Astronomical Observatory, Volgina 7, 11000 Belgrade, Yugoslavia
E-mail lpopovic@aob.bg.ac.yu

Abstract. The spectral line shape investigations of the Active Galactic Nuclei are carried out at the Belgrade Observatory since 1994. Initially the researches were only theoretical, the object of them having been the effects of the gravity field on the spectral line shapes. Subsequently these researches were extended to include the analysis of the observed emission spectral lines. On the basis of this analysis of the observed spectral lines the modelling was undertaken of the emission regions of the Active Galactic Nuclei. Special attention was paid to the investigation of time variations of these emission lines which point to the existence of two broad line emission regions in these objects.

1. INTRODUCTION

The investigation of the spectral line shapes and parameters helps us to understand the physical conditions and state of the plasma from which these are coming. In fact the only way of making diagnostics of plasma outside of the Solar System is the investigation of its radiation (spectral lines and continuum). The investigation of the spectral line shapes and parameters is very important also because most of the information on the celestial objects is acquired just by analyzing these parameters.

Among the most interesting objects in the Cosmos are Active Galactic Nuclei (AGN). These objects, where to the quasars also belong, are powerful radiation sources, one of their characteristics being the presence in their spectra of the very strong emission lines. These emission lines are characteristic of the active galaxies and in some of them a classification was deducted according to the shapes of these lines. For instance Syfert galaxies with narrow spectral lines (full width at the half maximum - FWHM - about several hundreds km/s) belong to the type two - Sy 2, while those with the broad lines (FWHM - up to several thousand km/s) belong to the type one - Sy 1.

According to the widely accepted view in the center of these objects there is a black hole with the accretion disk around it. This system is enveloped by an emission region. On the basis of researches in the spectral lines of these objects (see e.g. Osterbrock 1989) it has been brought out that the emission region from which they originate might be divided into several parts, each one with different physical properties. Generally two such regions are noticeable:

1. Broad line region (BLR) from which broad, mainly hydrogen and helium lines are radiated. This region is embedded in the environment of the accretion disk, its

dimensions being less than one parsec. It is composed of dense matter - a cloud, which in addition to the dominant rotation motion have their proper motion as well. The velocities of these clouds, derived from the lines half widths, run on the average around several thousand km/s (see e.g. Osterbrock 1989). The electron concentration in this region runs from 10^7 cm^{-3} to 10^{11} cm^{-3}, with temperature of about 10000 K.

2. Narrow line region (NLR) out of which narrow lines are coming, is larger, amounting to several kiloparsecs. It is from this region that radiation of highly ionized emitters (O III, C IV) is coming forth. Noticeable are also the lines from the forbidden transits (e.g. O III[4959,5007]). Otherwise the concentration of the emitters in this region is very slight, running from 10 cm^{-3} to 10^3 cm^{-3}.

Certainly, speaking strictly, the emission region is much more complex. For instance our investigation of the narrow line region in the Mkn 817 galaxy showed it to be composed of two parts (Popović and Mediavilla 1997). Sometimes one might include in the emission region the disk too, i.e. the disk effects may make themselves felt in the spectral line shapes, as is the case with the III Zw 2 (Popović et al. 1997).

The investigations of the spectral line shapes in Syfert galaxies and quasars at the Belgrade Observatory were started in 1994. The initial investigations were theoretical and connected with the gravity field effect on the spectral line shapes (Popović and Vince 1994, Popović et al. 1994ab, Atanacković et al. 1994, Popović et al. 1995a). Later on these investigations were extended to include the studying of the spectral lines shapes observed at the Crimean Astrophysical Observatory (Popović 1996). Here a condensed survey of researches performed at the Belgrade Observatory is given. These researches are carried out within the framework of the task *Investigation of the Spectral Line Shapes in Active Galactic Nuclei* which forms a part of the Belgrade Observatory's Research Project.

2. GRAVITATIONAL EFFECTS ON THE SPECTRAL LINES SHAPES

Researches concerning the influence of gravitational effects on the spectral line shapes in AGN promoted studying the nature of these objects at the Belgrade Observatory. Having regard to the model of the AGN which envisages a black hole in the nucleus centre, with region emitting the lines, the so called Broad Line Region (BLR), in the immediate vicinity of the black hole, i.e. in a strong gravitational field, one may expect this field to affect the emitted radiation coming from these objects. In what sense? First, the observed line having been obtained as a summary radiation of a cloud situated in the line of sight at different distances from the center, i.e. within different gravitational fields, the radiation emitted from particular clouds has different gravitational shifts. In other words, the radiation of those clouds situated closer to the center will be shifted toward the red with respect to the radiation of clouds more distant from the black hole. Of course, we must thereby keep in mind that we, as observers, are within a relatively weak gravity field with respect to the emitters situated within a Broad Line Region or within the accretion disk of the AGN. In any case this will lead to the distortion of the spectral line shapes of these objects. Second, the emitters will be in a strong gravitational field which must be taken into account at computing the atomic parameters of the emitter (oscillator strength, transition probability and line strength).

As already related, the initial investigations were connected with the effect of the gravitational redshift on the emission spectral line shifts for the case of the undistorted Lorentz profile (Popović and Vince 1994, Popović et al. 1994ab) and Voight profile (Atanacković et al. 1994, Popović et al. 1995a). In both cases analytical expressions were derived serving for accounting for this effect.

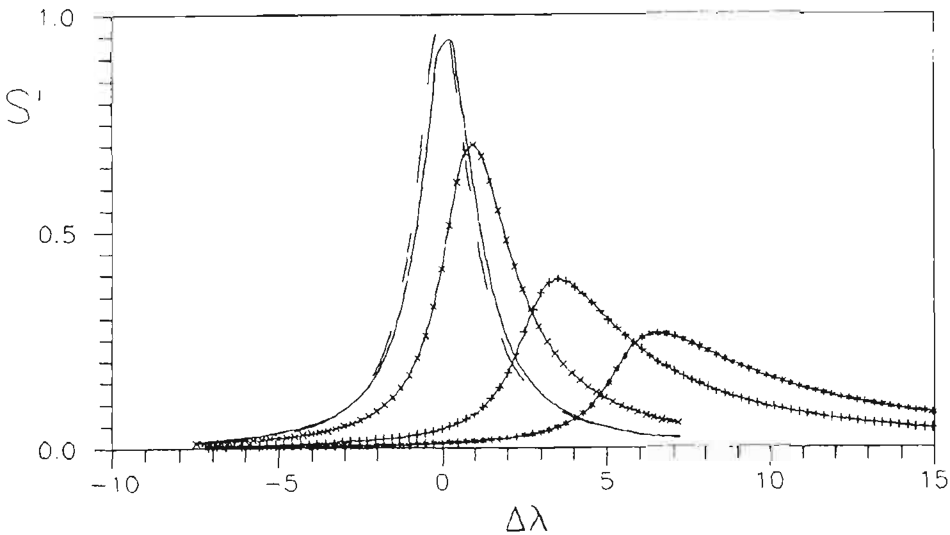

Fig. 1. The shape of the distorted spectral line profile for different transition lengths λ_0, compared with undistorted Lorentz profile (dissected line). (—) for λ_0 =1000 Å (solid line), $(-x-x)$ for λ_0 =10000 Å, $(+-+-)$ for λ_0 =50000 Å, $(-*-*-)$ for λ_0 =100000 Å. $\Delta\lambda$ expressed in Lorentz half-widths (Popović et al. 1994a).

In the case of the undeformed profile of the emission line being Lorentz one ($S(\lambda)$) the analytical expression for the distorted profile ($S'(\lambda, r, M)$) due to the unequal gravitational shift is (Popović & Vince 1994, Popović et al. 1994a)

$$S'(\lambda, r, M) = S(\lambda) \cdot \Phi(\lambda, r, M) \tag{1}$$

where $\Phi(\lambda, r, M)$ is the corrective factor depending on the distance of the region emitting the radiation from the black hole (r) and on the mass of the central object (M).

In the case of the Voight profile ($H(a, x)$) the expression for the distorted profile ($H'(a, x, r, M)$) is (Popović et al. 1995a)

$$H'(a, x, r, M) = \frac{a}{\pi} \int_{-\infty}^{+\infty} h(a, x, y) \cdot \Phi(a, x, y, r, M) dy \tag{2}$$

where $h(a, x, y)$ is the integrand of the Voight profile

$$h(a,x,y) = \frac{e^{-y^2}}{a^2 + (x-y)^2},$$

a is the relation of Lorentz and Doppler width and $x = \lambda - \lambda_0$ is expressed in Doppler half-width. The corrective function $\Phi(a, x, y, r, M)$ has the same analytical form as in the case of Lorentz profile.

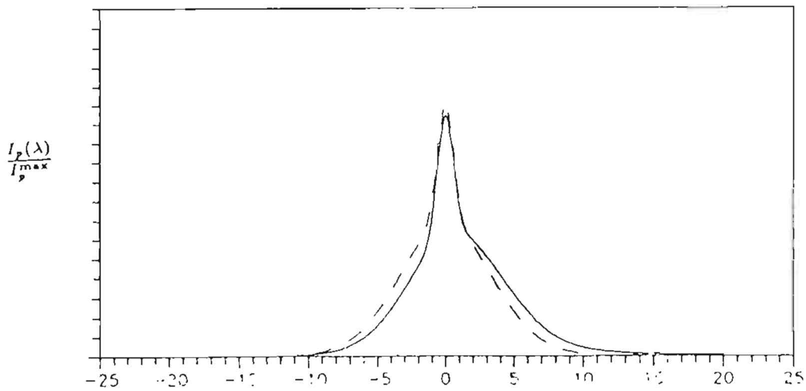

Fig. 2. The distorted H_β line in consequence of the gravitational effect (solid line) compared with the undistorted (dashed line). The model of an AGN is used, assuming the existence of three emission regions (Popović et al. 1995a).

The influence of the gravitational redshift effect on the spectral line shape was considered for optically thin and thick regions. The conclusion has been derived this effect to lead to the spectral line profile being distorted in such a way as to make the line broader, of lower intensity and shifted toward the red (Fig. 1.). This effect is more pronounced in the optically thin medium, which in fact applies to the broad line region situated closer to the black hole (Corbin 1997). In active galactic nuclei the distortion of the emission lines should be noticeable in the broad component, while this in the narrow component is not present. The investigations of other authors, made later on, give similar results (Corbin 1995, 1997ab).

Relatively recently investigations were started connected with the gravitational field effect on the atomic parameters of the emitter (Popović 1997, Popović 1999). Namely, for an observer situated in a weak gravity field, the radiation of the emitter will be shifted toward the red, i.e. the observer will find, by comparing the quantum system within a strong gravity field with one within his own field, the energy levels to differ according to

$$E_i' = E_i + \Delta E_i, \tag{3}$$

where E_i are quantum system levels energies in the observer's medium and E_i' are energies of the quantum system level whence the radiation is coming. ΔE_i is the energy difference depending on the difference of the gravitational field strength. This difference can be calculated for the active galactic nuclei knowing the value of the gravitational redshift to obey (Popović 1999ab)

$$\Delta E_i \approx -\frac{z_G}{1+z_G} E_i, \qquad (4)$$

where z_G is the gravitational shift. Actual calculations of the oscillator strengths and the transition probability were accomplished for the case of Ly_α line and the resonant $C\ IV$ lines (Popović 1999a). These lines are intensive in the UV spectrum of the AGNs.

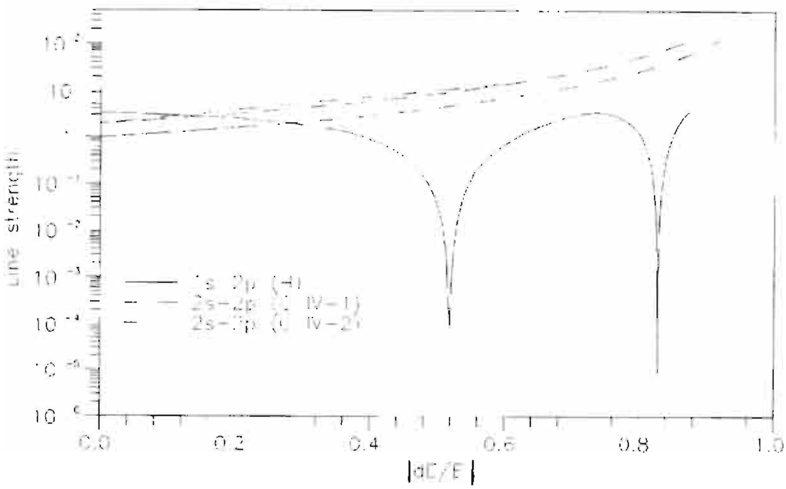

Fig. 3. Line strengths (in atomic units) for Ly_α (solid line) and resonant $C\ IV$ lines (dashed lines) (Popović 1999).

This effect ought to be taken into account at modelling the accretion disk and the broad line region in AGNs. This effect can equally be important in neutron stars.

3. ANALYSIS OF THE OBSERVED EMISSION LINE PROFILES IN ACTIVE GALACTIC NUCLEI

Upon theoretical consideration of the gravity field effects on the shapes and parameters of the spectral lines in active galaxies, it was natural to experimentally test these results. For this purpose it was necessary to analyze the profiles of the observed lines in the spectrum of Sy 1 galaxies or quasars in whose total line profile there is a pronounced broad line region and/or accretion disk. The first such investigation was the analysis of Ly_α line in the spectrum of the Mkn 335 galaxy obtained with the Hubble space telescope (Popović et al. 1995a). For that purpose the complex profile of Ly_α was decomposed into two Gauss components. It appeared that the broad component was shifted toward the blue part of the spectrum. On removing the narrow component from the observation a profile was obtained displaying red asymmetry (Fig. 4). In order to account for such profile a model was formed in which the cloud radiations were summed, the clouds being situated in different gravitational fields. Assumed thereby was very strong matter ejection, i.e. the clouds moving toward the observer. Such a model involving gravitational field effect, gave good agreement with the profiles observed in the Mkn 335 galaxy (Popović et al. 1995b).

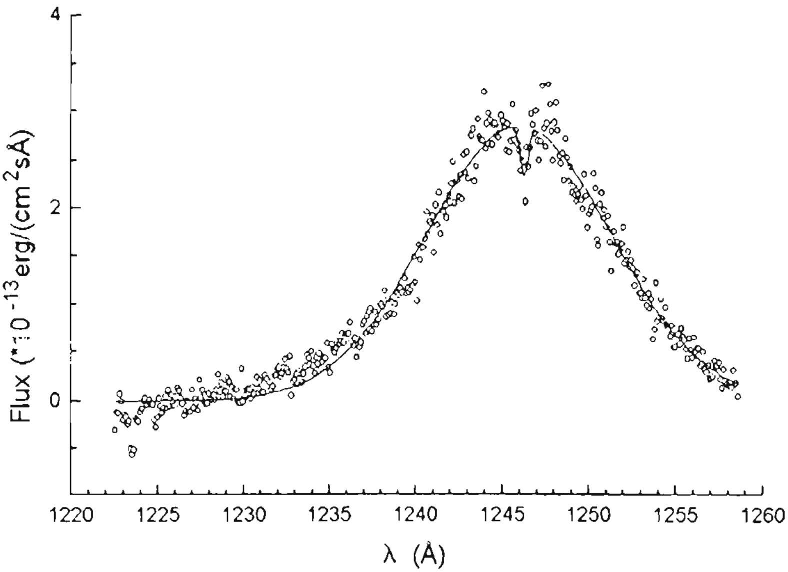

Fig. 4. Broad line component of Ly_α line in Mkn 335; the points represent the observations, the solid line illustrates the syntetized profile for which use has been made of the Broad Line Region model, with gravitational effects taken into account (Popović 1995b).

The need to acquire the observing material, i.e. the observations of larger number of galaxies in the H_β line in order to bring out this effect beyond doubt, through analysis of the observed profiles, investigated the processing of a great number of spectrograms of the Crimea Astrophysical Observatory (Popović 1996). Out of this material for the analysis were taken the spectra with the H_β lines of three Sy 1 galaxies in order to establish the effects of the gravitational field on these lines. Why exactly spectral region around H_β line was chosen? In the first place due to the fact that in the narrow span of the wavelengths in the environs of the wide H_β line and two narrow ones there are O III [4959,5007] lines coming almost exclusively from the Narrow Line Region. This renders it possible to introduce into analysis of the observed profiles, accomplished by fitting the observed lines by Gauss profiles, additional restrictions so as to minimize the possibility of false conclusions on the emission regions.

The following assumptions were introduced in the analysis performed by Gaussian profiles (Popović and Mediavilla 1997):

1. In view of the fact that the emission region is composed of several parts, the H_β line was fitted using at least three Gauss components which, coming from different parts, have different widths, shifts and intensities.
2. Binding together was made of the narrow line components of the broad H_β line and narrow O III [4959,5007] lines. It was namely assumed, having regard to their coming from the same region, that the narrow components have the same shifts and that their half-widths (ΔW) are mutually related according to

$$\frac{\Delta W_{H_\beta(NLR)}}{4861} = \frac{\Delta W_{4959}}{4959} = \frac{\Delta W_{5007}}{5007}.$$

3. Considering that the two O III lines are within the same multiplet, it has been assumed their intensities to be mutually related as their strengths in the line

$$\frac{I_{5007}}{I_{4959}} \approx 3.03$$

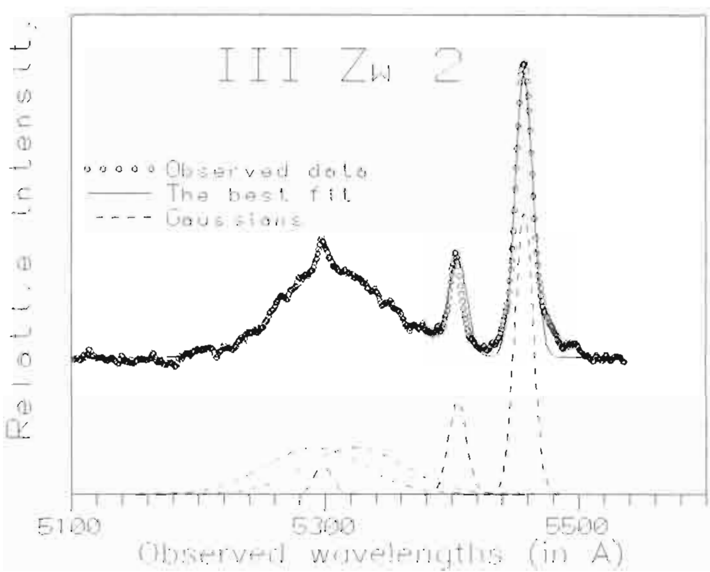

Fig. 5. The profiles associated with H_β + O III [4959,5007] III Zw 2 decomposed into components. Clearly noticeable two peaks of H_β point to a disk radiating in the H_β range.

Analysis has been made for three active galactic nuclei III Zw 2, 3C120 and Mrk 817 (Popović 1997a). These three objects were chosen because no fast and great changes in the line shapes have been noted. Besides, we deal here with Sy 1 galaxies and quasars in which one may expect the gravity effect to be noticeable. Use was made of the observations made at the Crimea Astrophysical Observatory covering a longer time interval. The spectra have been meaned whereby the spectra covering a shorter time period were summed in order to neutralize the noise arising in consequence of short period changes. The spectra thus obtained were analyzed striving thereby to decompose the H_β in all the spectra into the same number of components. The analysis of the observed profiles of three active galactic nuclei revealed the broad line component to be generally shifted toward the red with respect to the component in the narrow line region, which is in accordance with our theoretical investigations. This is particularly evident in Mrk 817 and III Zw 2 (Popović 1997a, Popović et al. 1998a, 1999c). It is likewise interesting to indicate the existence in Mrk 817 of three emission regions (Broad Line, Intermedium Line, and Narrow Line Regions), while in III Zw 2 the effects in H_β line of a rotation disk was discernible, i.e. two distinctly separated broad line components are noticeable.

4. INVESTIGATION OF CHANGES IN THE LINE PROFILES

In view of the extensive observing material at the Belgrade Observatory acquired with the 2.6 m telescope of the Crimean Astrophysical Observatory by K.K. Chuvaev, the investigations of the spectral lines were extended to include the changes of the line shapes over a longer time interval. An analysis was namely made of the H_β profile associated with Akn 120 (Popović et al. 1998b). The line profile in this galaxy are very variable, an indication of the stormy reactions in the BLR. It proved that the H_β profile in this galaxy is well described by a three region model. One of them is narrow line and two broad line ones.

In the H_β line of Akn 120 in the red portion there is a very broad component which varies considerably, probably belonging to the iron lines and to the broad O III lines (the broadest component in Fig. 6).

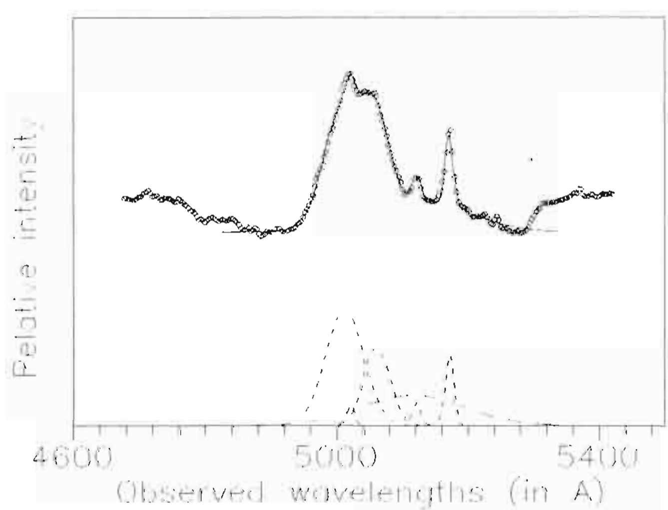

Fig. 6. The H_β profile in Akn 120 contains two broad line components. The circles represent the observed values. The solid line is the best fit. The dashed lines are Gauss components.

These investigations of the long period and the short period changes turned the attention toward the type 3C390.3 objects, interesting because of the possibility of existence in their centers of a twin black hole (Gaskell 1996). Having at our disposal the observations of the H_β line of 3C390.3 quasar, covering a longer time interval, led us to start developing a theoretical model of a close twin black hole or, more exactly, of the close twin broad line regions (Popović et al. 1998c). These investigations are made for the purpose of accounting for the complex lines observed in 3C390.3 quasar and the objects emitting lines similar to those of this object.

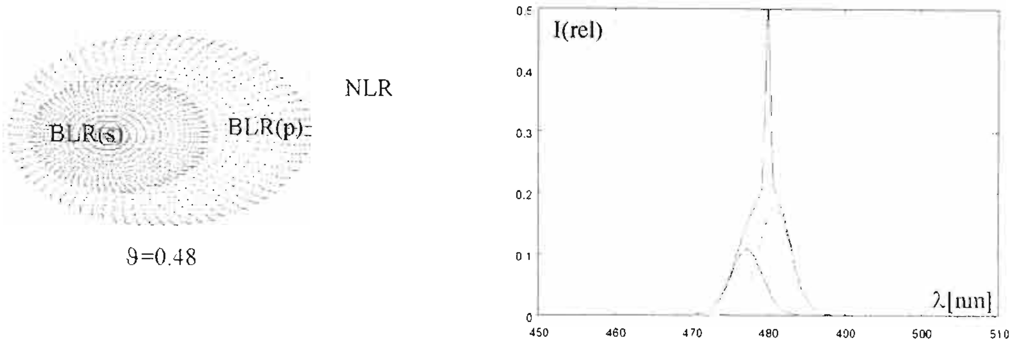

Fig. 7. The model of close twin broad line region (on the left) and shapes of the H_β line radiated by such a system (on the right). Labels: BLR(p), BLR(s) are broad line regions of the primary and the secondary, respectively; NLR - narrow line region. The narrow line peak steams from the NLR (Popović et al. 1998c).

The researches will be continued in the forthcoming period. First of all a developed theoretical model will be applied to H_β line of the 3C390.3 quasar whose observations cover a period of about twenty years (Popović 1996). On the other hand the H_β line shape of Akn 120 also points to the existence of two broad line regions, calling for further investigations.

Equally, the H_β line shape in III Zw 2 stimulated studies concerning the disk in this galaxy. For the purpose of determining the parameters of this disk the observations of this galaxy were made, according to our proposal, with the Isaac Newton Telescope (INT) in the Canary Islands. The processing of these observations, as well as the observations of the C IV and Ly_α lines of this galaxy, will provide more information on the nature of these objects.

References

Atanacković-Vukmanović O., Popović L. Č., Vince I. and Kubičela A.: 1994, *Bull. Astron. Belgrade* **150**, 1.
Corbin M. R.: 1995, *Astrophys. J.* **447**, 496.
Corbin M. R.: 1997, *Astrophys. J.* **487**, 517.
Corbin M. R.: 1997, *ASP Conference Series* **113** (eds. B. M. Peterson, F.-Z. Cheng and A. S. Wilson), p.260
Gaskell C. M.: 1996, *Astrophys. J. Lett.* **464**, 107.

Popović L. Č.: 1996, *Publ. Astron. Obs. Belgrade* **54**, 49.
Popović L. Č.: 1997, Abstracts of 29th EGAS (ed. H.-D. Kronfeldt), Technische Universität, Berlin, p. 516.
Popović L. Č.: 1997, Abstracts of JENAM - 97, (July 2–5), Thessaloniki, Greece, p.197
Popović L. Č.: 1999a, *Serb. Astron. J.* **159**, to be published
Popović L. Č.: 1999b, in preparation
Popović L. Č. and Vince I.: 1994, Abstracts of IAU Sym. 159 *Active Galactic Nuclei across the Electromagnetic Spectrum*, p. 55.
Popović L. Č., Jevremović D., Vince I. and Milovanov T.: 1995, *Publ. Obs. Astron. Belgrade* **50**, 107 - 110.
Popović L. Č., Vince I. and Kubičela A.: 1994a, In *Multi-Wavelength Continuum Emission of AGN* (eds. T.J.-L. Courvoisier and A. Blacha) p. 456.
Popović L. Č. and Mediavilla E.: 1997, *Publ. Astron. Obs. Belgrade* **57**, 95.
Popović L. Č., Salim S. and Vince I.: 1997, Abstract book of GA IAU 27, Kyoto (August 17 - 30), p.190
Popović L. Č., Pavlović R., Živkov V., Djurašević G. and Kubičela A.: 1998c, *19th SPIG, August 31 - September 4, 1998, Zlatibor*, Contribution, (eds. N. Konjević, M. Ćuk and I. R. Videnović), Faculty of Physics, University of Belgrade, Belgrade, p.639.
Popović L. Č., Trajković N. and Kubičela A.: 1998a, *Publ. Astron. Obs. Belgrade* **60**, 67.
Popović L. Č., Trajković N., Kubičela A., Doroshenko V. T., Sergeev S. G., Bon E. and Stanić I.: 1998b, *Publ. Astron. Obs. Belgrade* **61**, 139.
Popović L. Č., Vince I., Kubičela A. Atanacković-Vukmanović O. and Samurović S.: 1994b, *Bull. Astron. Belgrade* **149**, 9.
Popović L. Č. Vince I., Atanacković- Vukmanović O. and Kubičela A.: 1995a, *Astron. Astrophys.* **293**, 309.
Popović L. Č., Vince I., Kubičela A., Salim S.: 1999, Proceedings of IAU Symp. No. 184 (Aug. 18-22 1997, Kyoto), *The Central Regions of the Galaxy and Galaxies*, to be published.