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Nuclear activity in the barred spiral galaxy NGC 3660 from radio, optical, and X-ray observations

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Summary. We report on radio, optical, UV, and X-ray observations of the barred spiral galaxy NGC 3660. This object is one of our program galaxies within a systematic study of activity in a complete sample of barred spirals. The application of various criteria involving observational results in different spectral ranges identifies NGC 3660 as a transition object between Seyfert 1 galaxies and narrow emission line galaxies (NELG's). NGC 3660 shows a rich emission line spectrum with ionization stages up to Fe XIV. This galaxy may therefore be regarded as a good example for a high ionization narrow emission line region galaxy.

Key words: active nuclei – barred spirals – X-ray, radio, optical observations

1. Introduction

In a systematic spectroscopic study of barred galaxies we investigate the role played by central bars for the occurrence of nuclear activity. Effective feeding of a nuclear source is expected as a consequence of non-axisymmetric distortions in the central regions of such galaxies (cf. e.g. Norman and Silk, 1982). A strong correlation between both phenomena is suggested by the observation that many Seyfert galaxies are barred spirals (Adams, 1977) and that in radio continuum surveys of complete samples of normal galaxies barred spirals have stronger than average nuclear radio emission (Hummel, 1980, 1981). Here we report on radio, optical, UV and X-ray observations of one of our program galaxies, the bright SBbc galaxy NGC 3660 showing nuclear activity. At a distance of 69 Mpc ($H_0 = 50$ km s^{-1} Mpc^{-1}) its angular diameter of $2\overset{'}{.}8$ (RCBG2, de Vaucouleurs et al., 1976) implies the large extension of 56 kpc.

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NGC 3660 has an optical magnitude of $\sim 11^{\text{m}}9$ in B (Vorontsov-Velyaminov and Arhipova, 1968; Nilson, 1974). Its 1950 position is $\alpha = 11^{\text{h}}21^{\text{m}}00\overset{\text{s}}{.}5$, $\delta = -08°23'16''$.

2. Observations

a) Radio observations

NGC 3660 has been observed with the 100 m radio telescope of the MPIfR at Effelsberg in the continuum at 5 GHz in January 1982. The object was detected with a flux density of 11 ± 2 mJy. NGC 3660 has also been detected in the H I 21 cm line with a flux in the line of 26 ± 5 Jy km s^{-1} corresponding to a neutral hydrogen mass of $3\ 10^{10}\ M_\odot$.

b) Optical and ultraviolet observations

The optical observations were made on Dec. 21, 1981, Feb. 19, and March 1, 1982 at the ESO 1.52 m and 3.60 m telescopes using the IDS attached to the Boller and Chivens spectrograph. A total optical wavelength range from 3700 to 7150 Å is covered by our spectra. Data relevant to the optical observations are compiled in Table 1. The seeing was $1''-2''$. The fluxes were calibrated from observations of white dwarfs standards (Oke, 1974) during the same nights. The spectra were reduced in the standard way at ESO/Garching and USG.

The wavelength region 1200–1950 Å was observed with the IUE satellite on Feb. 25, 1982 in the low resolution mode for 80 min. From this SWP spectrum (No. 16422) we derived a UV flux $F_\lambda = (2 \pm 1) \cdot 10^{-15}$ erg cm^{-2} s^{-1} Å^{-1} approximately constant over the short wavelength range.

c) X-ray observations

NGC 3660 was observed with the EINSTEIN X-ray observatory on Dec. 20, 1980 with the IPC for 5925 s. After calibrations and

Table 1. Optical observations

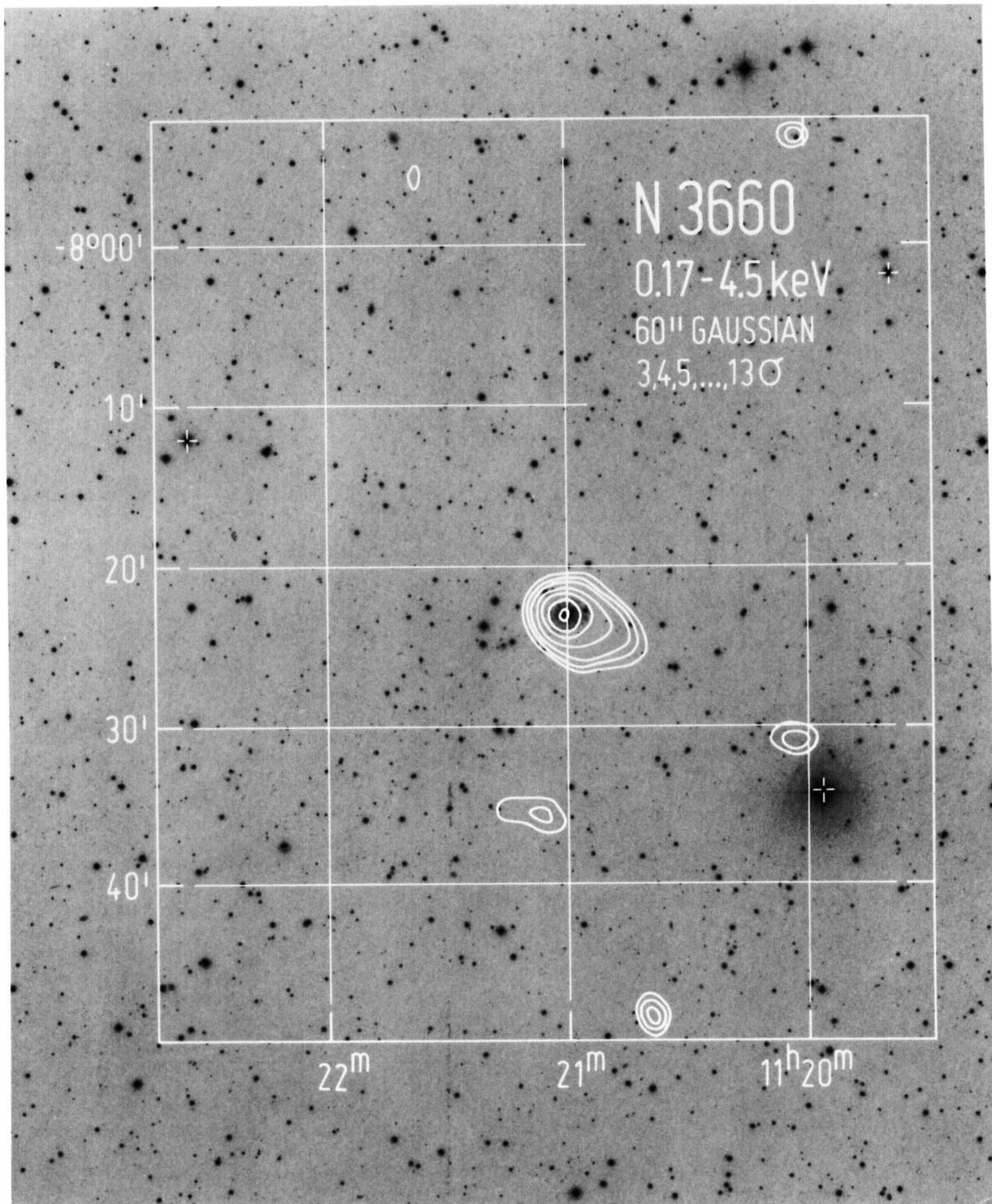| Telescope	Date of observation	Exp. time [min]	Spectral range [Å]	Dispersion [Å/mm]	Diaphragm
3.60	81/12/18	20	4100–7150	172	$4'' \times 4''$
1.52	82/2/19	20	4860–7000	114	$8'' \times 8''$
3.60	82/3/1	12	3700–7150	172	$4'' \times 4''$

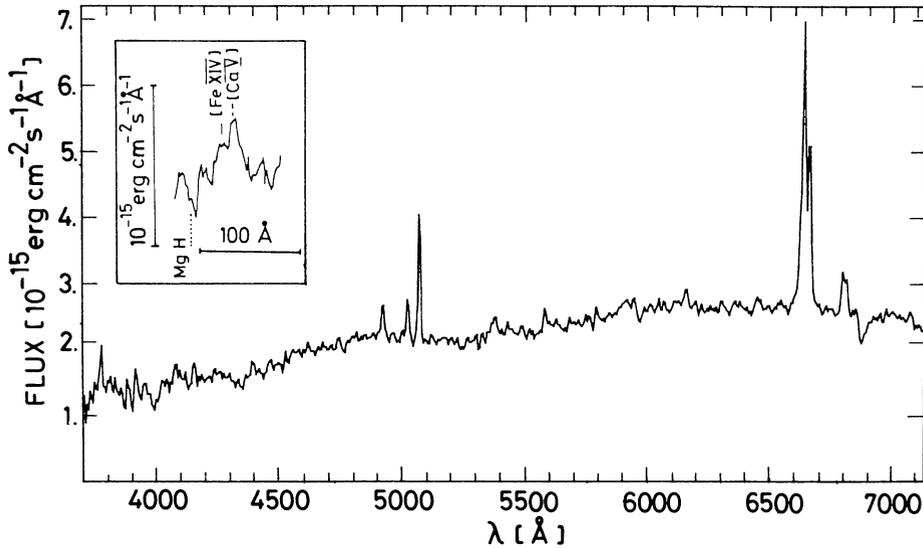**Fig. 1.** The X-ray map of NGC 3660 superimposed on the POSS

Fig. 2. The optical spectrum of NGC 3660. The inset shows with better resolution the spectral region around [Fe XIV] 5303 (solid line). Also the positions of the [Ca V] 5309 line (dashed line), and of the MgH 5269 absorption band (dotted line) are indicated

background subtractions smoothed contour maps were obtained using the standard EINSTEIN Observatory reduction software at CFA, Harvard. The background was determined from a concentric ring ($200''$–$440''$ radius). An overlay of the X-ray map with the POSS for the energy range 0.17–4.5 keV is shown in Fig. 1. The slight extension of the X-ray image is probably due to an unrelated star-like object.

Using the H I column density of $3.9 \, 10^{20} \, \mathrm{cm}^{-2}$ in our galaxy from Heiles (1975) and an assumed energy spectral index $\alpha = -0.7$ ($S_\nu \propto \nu^\alpha$) typical for narrow emission line galaxies (Maccacaro et al., 1982) we obtained an X-ray flux in the energy range 0.5–4.5 keV of $5.3 \, 10^{-13} \, \mathrm{erg} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$. This corresponds to 46 nJy at 2 keV and an X-ray luminosity of $3.2 \, 10^{41} \, \mathrm{erg} \, \mathrm{s}^{-1}$. This flux value is probably close to the intrinsic X-ray flux from the nucleus, since NGC 3660 is nearly face-on and its H I column density to the center estimated from our 21 cm line observations is rather low ($\sim 6 \, 10^{20} \, \mathrm{cm}^{-2}$) and early type galaxies tend to have less than average column density of neutral gas (H I and molecules) near the center than later Hubble type galaxies (Young and Scoville, 1982).

3. Results

3.1. Overall energy distribution

In Fig. 3 the known continuum spectrum of NGC 3660 is represented from the radio to the X-ray spectral ranges. The optical continuum fluxes have been derived from the spectrum obtained on March 1, 1982. Optical and UV continuum were corrected for reddening within the Galaxy adopting $E_{B-V} = 0.031$ (Burstein and Heiles, 1978). The slope of the optical spectrum is ~ -3 and of the UV spectrum ~ -2. The spectral slope between optical and X-ray frequencies is $\alpha_{0x} \sim -1.7$ which is somewhat steeper than the average effective slope found for quasars by Zamorani et al. (1981).

The application of photoionization theory permits to determine the slope α_{ion} of the ionizing continuum incident on the gas between the He II ionization edge (228 Å) and the Lyman edge (912 Å) via the line ratio He II 4686/Hβ (cf. Penston and Fosbury 1978) whereby complete absorption of this portion of the continuum by lines is assumed. In NGC 3660 this ratio is 0.33 which is high compared to normal NELG's. Theoretically, this ratio is in terms

of α_{ion} given by $2^{2\alpha_{\mathrm{ion}}+1}$. Thus, $\alpha_{\mathrm{ion}} \simeq -1.3$ which is close to α_{0x} above.

3.2. Optical line spectrum

a) Line identifications

The optical spectrum is shown in Fig. 2, from which we derive a redshift of NGC 3660 $z = 0.0115 \pm 0.0004$ (corrected for solar motion). Table 2 contains the relative intensities (H$\beta = 1$) of the emission lines identified from [O II] 3727 through [S II] 6731. Estimated relative errors are 10–20 % for strong lines and 50 % for weak lines. All lines (forbidden and permitted) were dereddened by assuming the intrinsic case B Balmer decrement (Osterbrock, 1974). The line spectrum contains highly ionized Fe lines as, e.g., in IIIZw 77 (Osterbrock, 1981), which are rarely observed. The coronal line [Fe XIV] 5303 can clearly be separated from the [Ca V] 5309 line in our spectrum (cf. Fig. 2, inset) like in Osterbrock's (1981) spectrum. In our spectrum the [Fe XIV] 5303 line is blueshifted relative to the [Ca V] 5309 line by ~ 11 Å corresponding to $\Delta z \simeq -2 \, 10^{-3}$. The phenomenon that the high ionization Fe lines are blue-shifted with respect to the lower ionization permitted lines has been noted earlier by Shuder (1980) in NELG's and by Grandi (1978) and Osterbrock (1981) in Seyfert galaxies. These authors interpret this effect in terms of relative motions between the places of origin for widely separated ionization stages.

Also the [Fe X] 6374 line is present in our spectrum. The contamination of this line with [O I] 6363 will be negligible since the latter is expected to be three times weaker than [O I] 6300 which is already near the detection limit. [Fe VII] 6087 coincides with [Ca V] 6087. Theoretically, this line has only 20 % of the strength of the [Ca V] 5309 line and is therefore relatively weak. Together with [Fe VII] 6087 also [Fe VII] 5721 and [Fe VII] 5278 are often present. In our spectrum of NGC 3660 these lines are superimposed on the galactic absorption features Mg I 5710 and MgH 5269.

The [Fe VII] and [Fe X] lines also show a slight tendency of being blueshifted with respect to the permitted lines. There is marginal evidence in the spectrum for the appearance of the higher Balmer lines (Hδ–H9) in absorption which would imply the presence of a component of hot young stars in NGC 3660 (cf. Ward et al., 1980).
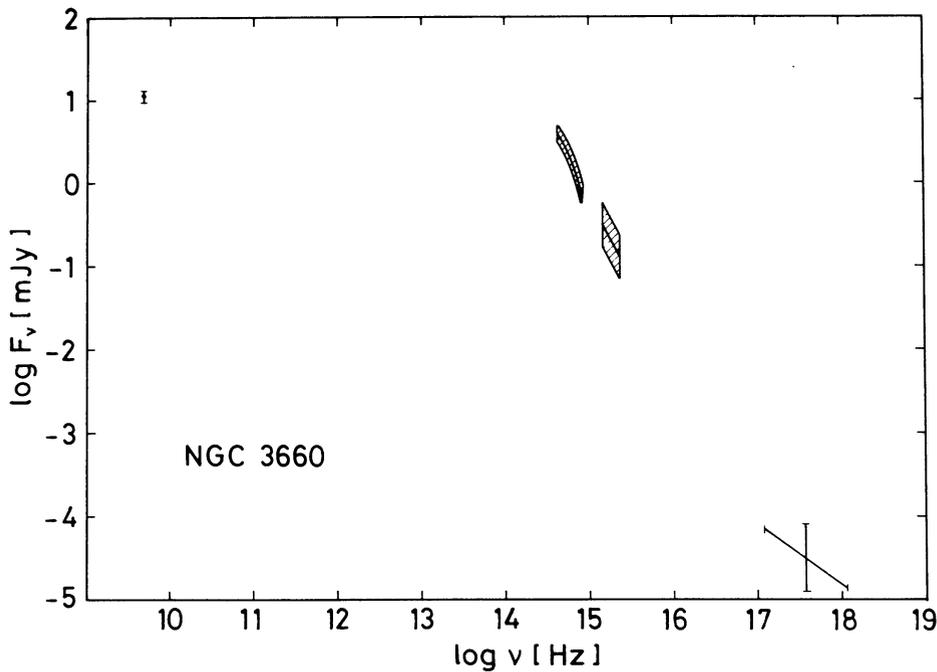
Fig. 3. Continuum flux density measurements at radio, optical, ultraviolet, and X-ray wavelengths for NGC 3660

Table 2. Emission line intensities

		$[F/F_{H\beta}]^{observed}$	$[F/F_{H\beta}]^{dereddened*}$
[OII]	3727	.94	2.41
[NeIII]	3869	.48	1.06
Hδ	4102	.44:	.82:
Hγ	4340	.27	.42
[OIII]	4363	.12	.18
HeI	4471	.24	.34
HeII	4686	.28	.33
Hβ	4861	1.	1.
[FeVII]	4900	.19	.18
[FeVII]	4942	.18	.17
[OIII]	4959	1.08	1.00
[OIII]	5007	3.18	2.80
[NI]	5199	.14	.10
[FeXIV]	5303	.16	.11
[CaV]	5309	.50	.38
[FeVII]	5721	.27	.14
HeI	5876	.36	.17
[FeVII]	6087	.57	.23
[FeX]	6374	.32	.11
[NII]	6548	1.67	.54
Hα	6563	8.79	2.84
[NII]	6583	4.23	1.36
[SII]	6716	.95	.29
[SII]	6731	.88	.27

$H\beta^{observed}$: $1.07 * 10^{-14}$ erg cm^{-2} s^{-1}

*dereddening with $E_{B-V} = 0.031$ (Galactic) and $E_{B-V} = 1.025$ (instrinsic).

b) Line ratios and physical conditions

The line ratio [OII 3727]/[OIII 5007]=0.86 is compatible with power law photoionization (cf. Baldwin et al., 1981; Ferland and Netzer, 1982). The usual diagnostic indicators of the photoionization theory are applied: From [OIII (4959+5007)]/[OIII 4363]=21.2 an electron temperature T_e=30.500 K is derived for the O^{++} zone in the limit n_e=0. The ratio [NII (6548+6583)]/[NII 5755]=141.9 yields T_e=8510 K for the N$^+$S$^+$-zone in the limit n_e=0. Using this temperature the electron density has been determined for the N$^+$S$^+$-zone from [SII 6716]/[SII 6731]=1.07 resulting in n_e=1110 cm^{-3}.

4. Discussion and conclusions

The observational results described above provide in many ways evidence for nuclear activity in the emission line SBbc galaxy NGC 3660. We applied several criteria in order to assess the relation of this galaxy to normal and Seyfert galaxies:

The value 2.8 for the ratio [OIII 5007]/Hβ indicates that NGC 3660 is close to the border line between NELG's and Seyfert galaxies. For Seyfert galaxies this ratio is $\gtrsim 3$ (Shuder and Osterbrock, 1981). Similarly the position of NGC 3660 in the plot log Hα/[NII] vs. log [OIII]/Hβ turns out to fall right into the gap between the Seyfert galaxies and normal HII regions (Veron, 1981).

We compare the X-ray emission of NGC 3660 with that of normal galaxies, using Long and van Speybroeck's (1981) tabulation. In the $L_x - L_v$ diagram, NGC 3660 is close to active nuclei galaxies with a compact radio nucleus (cf. Dressel et al., 1982). The X-ray flux is thus likely to be dominated by nuclear emission.

The preceding argument may be strengthened by considering the luminosity ratio $L([OIII])/L_x$. The dereddened flux value for the [OIII 5007] line implies $L([OIII])=6.5$ 10^{41}erg s^{-1}. Comparison with Fig. 5 of Lawrence and Elvis (1982) shows that

NGC 3600 is among NELG's, intermediate Seyferts, and Seyfert 2 galaxies.

Using then the interpretation of the various kinds of Seyfert galaxies put forward by Lawrence and Elvis (1982) we can obtain an estimate for the hard X-ray luminosity (2–10 keV) from their Fig. 4. This leads to a hard X-ray luminosity of $6\ 10^{42}$ erg s^{-1} with an uncertainty of a factor of 2. We note that the interpretation of Lawrence and Elvis implies the presence of broad line wings of Hα, Hβ, and of other permitted lines. There seems to be indeed evidence for such broad wings in the spectrum of NGC 3660:

We compare the total profile of Hα + [N II 6548 + 6584] in NGC 3660 with that in NGC 2980. This NELG had been observed during the same night and under the same conditions. It shows the same line-complex to have markedly narrower wings than the one observed in NGC 3660. Thus, we suspect that a broad component in NGC 3660 of FWZI $\sim (4000 \pm 400)$ km s^{-1} is present.

Finally, the effective spectral slope between X-ray and optical frequencies (~ -1.7) and the spectral index in the UV (~ -1.3) as inferred from line ratios (cf. Sect. 3.1) are typical for active nuclei as well, much flatter than for normal galaxies.

In summary all these criteria classify NGC 3660 as a transition object between Seyfert 1 galaxies and NELG's. It is suggestive to assume that this activity is indeed a consequence of the presence of a central bar in this galaxy. Remarkable is the occurrence of very highly ionized Fe lines up to [Fe XIV]. The photoionizing radiation for these lines may well be provided by the observed X-ray flux. NGC 3660 is a good example for a high ionization narrow emission line region galaxy (HINER).

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