

Optical Investigation of the Spiral Galaxy NGC 660

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Summary. A photometric and spectroscopic study of the barred galaxy NGC 660 is presented. This object shows heavy absorption patterns and a complex morphology of the outer arms. From the analysis of the photographic material a tentative model explaining the morphology of the galaxy has been outlined. Apart from the peculiar aspect it was found that the overall photometric parameters are normal for this morphological type. At a distance of 12 Mpc and after correction for galactic absorption the total absolute blue magnitude of NGC 660 is $M_B = -18.76$.

From eight spectra at a dispersion of $125 \text{ \AA mm}^{-1}$, taken at different position angles, the velocity field of the main body is discussed and three possible interpretations are outlined for the discrepancy between the orientation of the photometric major axis and the kinematical line of nodes. An estimate of the mass within 1.7 kpc ranges between $6.5 \cdot 10^9 M_\odot$ and $8.2 \cdot 10^9 M_\odot$.

Key words: peculiar galaxies — morphology — photometry — dynamics

I. Introduction

NGC 660 (Fig. 1) is a relatively bright galaxy, its photographic magnitude being 11.8 (Holmberg, 1958). It shows a central body, possibly a bar, crossed by two systems of absorption, which will be discussed in the next Section. Two extended spiral arms originate from the extremes of the central bulge. The galaxy is classified SBa peculiar by de Vaucouleurs and de Vaucouleurs (1964). In the Morphological Catalogue (Vorontsov-Veljaminov and Krasnogorskaya, 1962) NGC 660 is described as a barred galaxy with two smooth spiral arms emerging at right angles with the bar.

To our knowledge no spectroscopic observations of this object have been published so far. No detected radio emission has been associated with NGC 660.

However there is the radio source OC 166 (Fitch et al., 1969) which is close to the galaxy. The radio position differs from the optical one, as derived from the list of Gallouët and Heidmann (1971), by 15 s in Right Ascension and 7' in Declination. This is within two probable errors of the radio position, as defined by Fitch et al. (1969), in Declination and three probable errors in Right Ascension. If the radio source is associated with the galaxy, the radio flux, with the Hubble distance of 12 Mpc, gives $\log P_{1415} = 20.77 \text{ W Hz}^{-1} \text{ Sterad}^{-1}$.

Since the peculiar structure of the absorption suggests the presence of H II regions and violent nuclear activity (and hence strong emission lines in the spectrum) we have included NGC 660 in our program of photometric and spectroscopic observations of peculiar galaxies (Barbon and Capaccioli, 1973; Benvenuti et al., 1975b).

II. Photographic Material

Several plates of NGC 660 through different color filters have been taken with the reflectors of the Asiago Observatory (see list in Table 1). The photographs, taken with the 122 cm reflector and matching the B band of the UBV system, have been calibrated by means of a spot sensitometer. The photographic material reproduced in Figure 1 clearly reveals the complex morphology of this galaxy. The main body is much redder than the outer arms as shown by the comparison of blue and red plates. It is crossed by two principal absorption features and defines a bar-like structure, whose spheroidal shape, with an axial ratio $b/a = 0.46$, is apparent from an inspection of the isophotal map of Figure 3. The inner spot structure of the bar, visible on light exposures both in blue and in red, is probably due to the patchy absorption spread over the galaxy. The nucleus seems relatively large and smooth, as is typical of early type spirals.

The blue outer arms extend out to 18 kpc from the center, assuming a distance of 12 Mpc. It seems difficult

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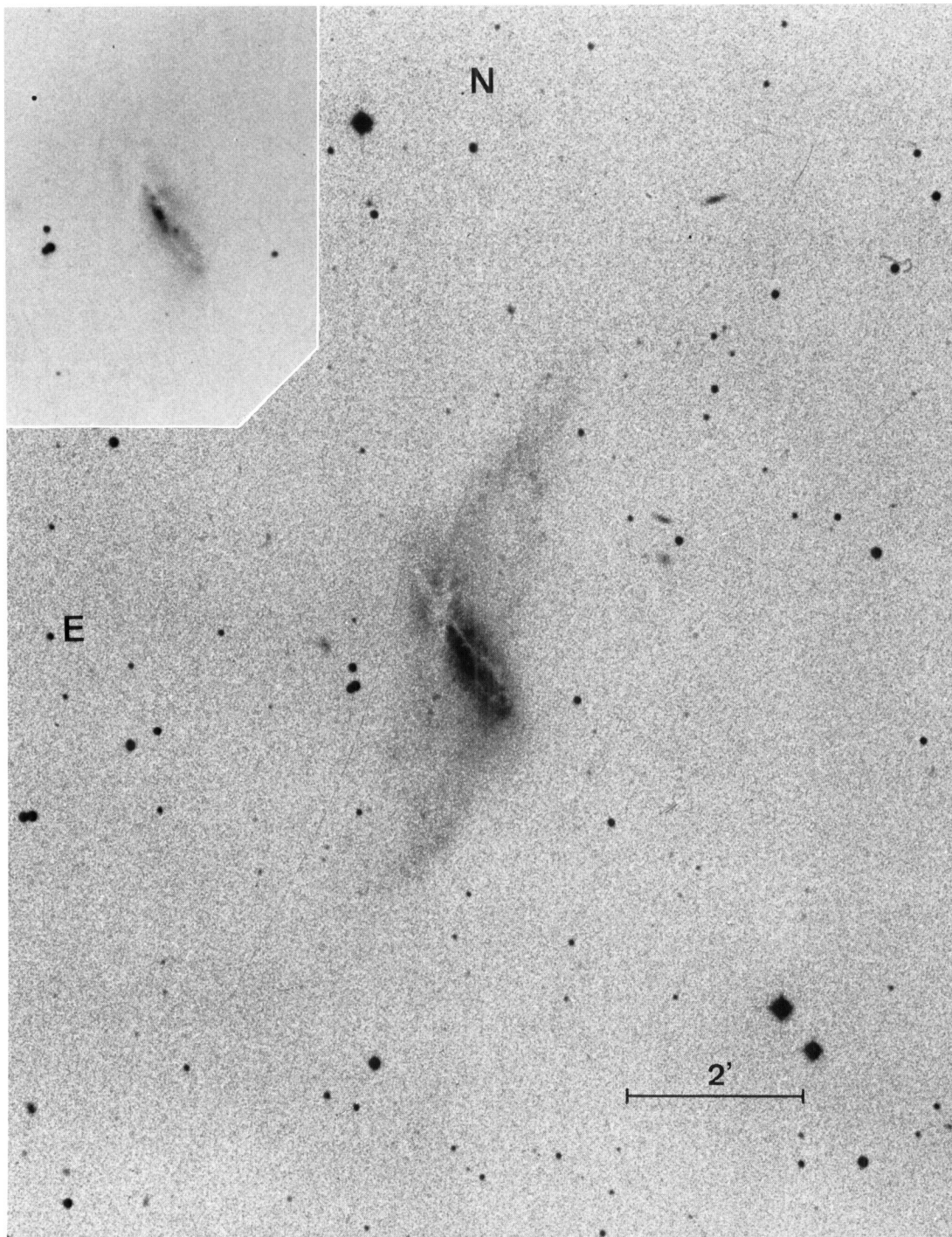


Fig. 1. NGC 660. Center: Blue photograph (103a-O+GG 13) taken with the 122 cm reflector (plate scale 34''/mm). Top: Light exposure of the inner part, 182 cm reflector (103a-O+GG 13, plate scale 12''/mm)

to fit to the photographic image of NGC 660 a model with the arms in the equatorial plane of the galaxy, wherever the latter is placed. As a working hypothesis (and being well aware that many other models could be tentatively suggested) we propose the model sketched in Figure 2, with two main arms emerging from the ends of the bar. These arms are shifted off the principal plane and wind around the galaxy. Shorter arms might also be present. In our model the long and thin absorption crossing the main body is interpreted as due to

residual dust in the equatorial plane, while the other one as due to arm II.

This peculiar structure is not very far from that observed in NGC 3628 (Barbon and Capaccioli, 1973). A possible interpretation, to be verified on a dynamical basis, could be that the bar is a three axis ellipsoid which rotates around both the minor axes. The principal plane, which contained the arms in an earlier stage, should be normal to the axis of major rotation. Geometric and tidal effects due to the small motion around

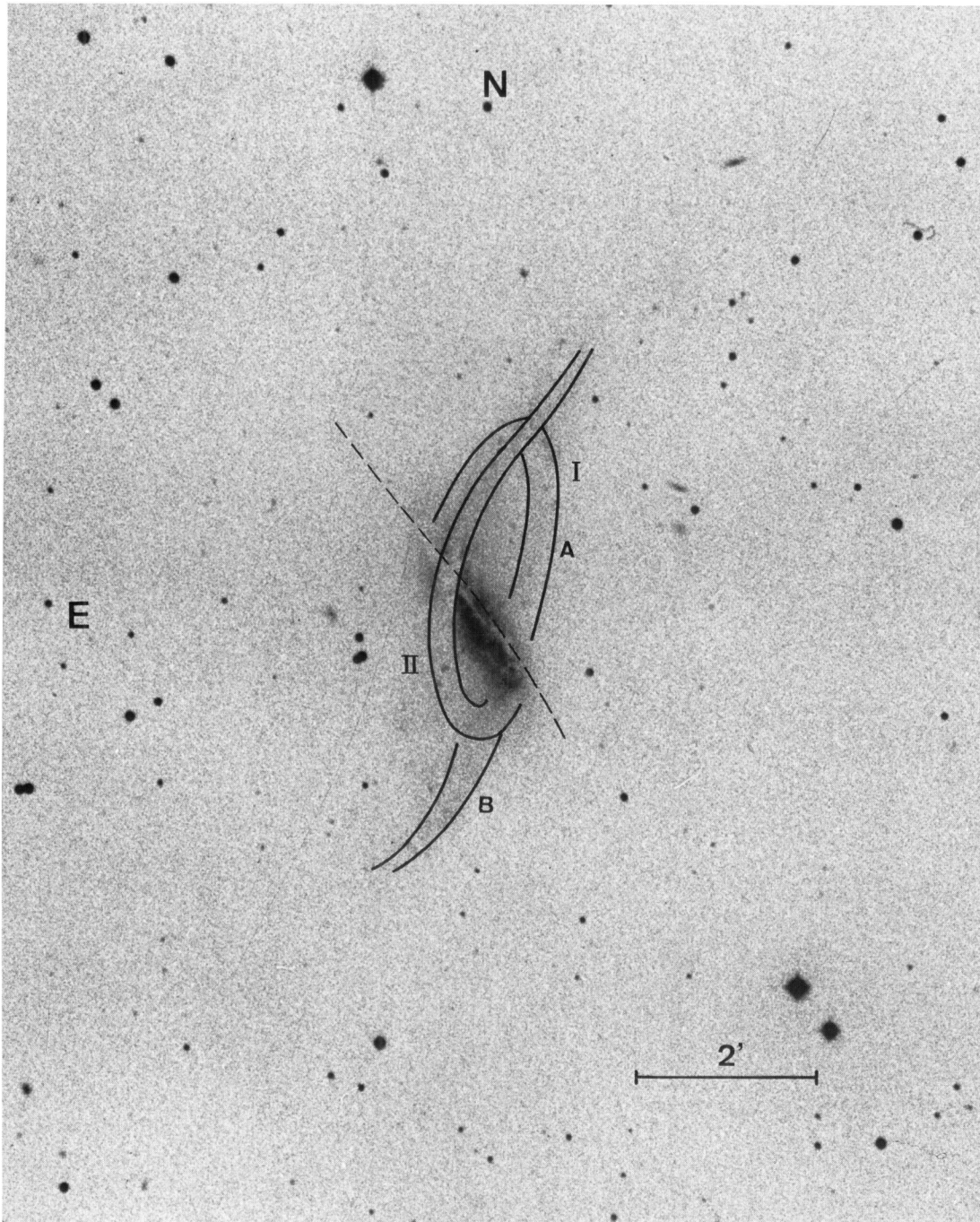


Fig. 2. NGC 660. Proposed model for the morphology of the outer arms (see the text)

Table 1. Photographic material

Plate No.	Date	T.U.	Emuls.	Filter	Exp.	Telescope	Scale
9166	8. 1.1973	18 ^h 15 ^m	103a-O	GG 13	10 ^m	122 cm refl.	34"3 mm ⁻¹
9167	8. 1.1973	18 ^h 38 ^m	103a-O	GG 13	30 ^m	122 cm refl.	34"3 mm ⁻¹
9168	8. 1.1973	18 ^h 56 ^m	103a-O	GG 13	5 ^m	122 cm refl.	34"3 mm ⁻¹
9169	8. 1.1973	19 ^h 49 ^m	103a-O	GG 13	80 ^m	122 cm refl.	34"3 mm ⁻¹
9170	8. 1.1973	20 ^h 41 ^m	103a-O	GG 13	15 ^m	122 cm refl.	34"3 mm ⁻¹
6143	28. 1.1973	17 ^h 53 ^m	103a-E	RG 1	45 ^m	Schmidt 67/95	95" mm ⁻¹
6144	28. 1.1973	18 ^h 35 ^m	103a-O	GG 13	25 ^m	Schmidt 67/95	95" mm ⁻¹
42	9. 8.1973	26 ^h 18 ^m	103a-O	—	30 ^m	182 cm refl.	12"6 mm ⁻¹
140	23.10.1973	22 ^h 52 ^m	103a-O	GG 13	30 ^m	182 cm refl.	12"6 mm ⁻¹
9269	23.11.1973	22 ^h 55 ^m	103a-O	GG 13	25 ^m	122 cm refl.	34"3 mm ⁻¹
9274	25.11.1973	20 ^h 37 ^m	103a-O	GG 13	105 ^m	122 cm refl.	34"3 mm ⁻¹

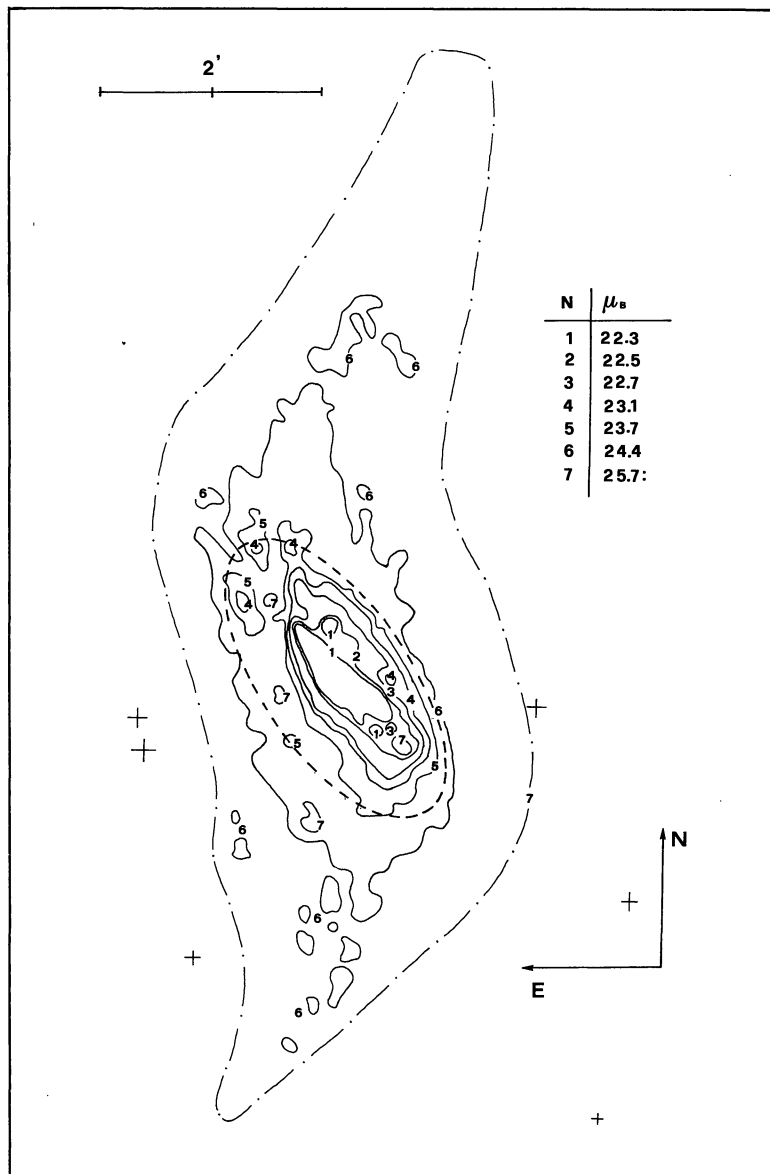


Fig. 3. NGC 660. Isophotes. Crosses are reference stars. The dashed ellipse represents a tentative representation of the main body of the galaxy

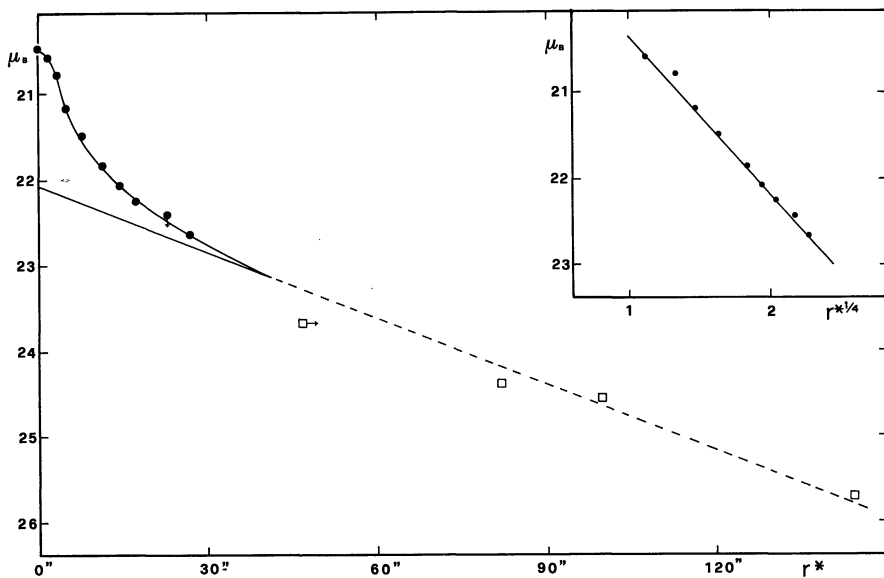


Fig. 4. NGC 660. Equivalent luminosity profile. Dashed line is the exponential interpolation of the measures in the outer disk. The inner measures, corresponding to the main body of the galaxy, follow the $r^{1/4}$ law, as shown in the inset

Table 2. Photometric parameters

Distance	$\Delta = 12$ Mpc
Sky unit	$\mu_s = 21.74$ mag arc s ⁻²
Total apparent B magnitude	$m_B = 11.97$ mag
Absolute B magnitude not corrected for absorption	$M_B = -18.43$ mag
Mean apparent axial ratio of the spheroidal component	$\langle b/a \rangle = 0.46$
Peak brightness of the exponential component	$B(O) = 22.1$ mag arc s ⁻²
Equivalent gradient of the exponential component	$\alpha^* = 4.41 \cdot 10^{-1}$ mag kpc ⁻¹
Effective equivalent radius	$r_e^* = 68''$
Luminosity within $\mu = 25$ mag arc s ⁻²	$K(25) = 0.73$

the other axis, together with a friction with the outer envelope, might produce the observed pattern of the spiral arms.

The fact that arm I, in the region marked A , is fainter than in the region B , can be explained with the presence of absorbing dust in that part of the arm facing the main body.

The surface photometry of NGC 660 in the B system was carried out using the calibrated plates listed in Table 1. The reduction procedure was the standard one described by Capaccioli (1973). Scans along six well spaced axes at P.A. 41° were used to calibrate the isophotal maps produced with the Joyce-Loebl microdensitometer of the Padova Observatory. Final isophotal contours are given in Figure 3. The zero point of the magnitude scale, i.e. the sky level, fixed by the comparison with the photoelectric observations published by de Vaucouleurs and de Vaucouleurs (1972), results $\mu_s = 21.74$ mag arc s⁻². From integration of the equivalent luminosity profile, shown in Figure 4, we obtain a total apparent blue magnitude $m_B = 11.97$ mag, in close agreement with the value quoted in the Reference Catalogue (de Vaucouleurs and de Vaucouleurs, 1964). With a distance of 12 Mpc and a correction for galactic absorption of 0.33 mag, the total absolute magnitude is -18.76 mag, thus placing NGC 660 in the range of relatively bright spirals. The standard photometric parameters are summarized in Table 2.

The equivalent luminosity profile is rather normal and typical of a spiral galaxy. The central bulge follows the $r^{1/4}$ law (inset in Fig. 4). The outer regions have an exponential trend which is poorly defined owing to the strong absorption patterns across the main body. A comparison with the statistical parameters derived by Freeman (1970) shows that the face-on absorption-free peak brightness of the exponential component of NGC 660, $B(O)_c = 22.65$ mag arc s⁻², is 1.0 mag fainter than expected. On the other hand, the gradient: $\alpha = 0.4 \alpha^*$ [mag kpc⁻¹] (b/a)^{1/2}/log₁₀ $e = 2.77 \cdot 10^{-1}$ kpc⁻¹, is within the range typical of this morphological type.

III. Spectroscopic Observations

Eight untrailed spectra of NGC 660 at different position angles were obtained with the image tube nebular

Table 3. Spectroscopic material

No.	P.A.	Exposure	Notes
1875	0°	80 ^m	nuclear emission only
2086	0°	90 ^m	nuclear emission only
2170	10°	90 ^m	[S II] $\lambda\lambda$ 6717–6731 Å present
2124	30°	90 ^m	[S II] $\lambda\lambda$ 6717–6731 Å present
1771	32°	75 ^m	extended emission NE of nucleus
1754	33°5	30 ^m	nuclear emission only
1852	33°5	75 ^m	extended emission NE of nucleus
1821	123°	50 ^m	nuclear emission only

spectrograph attached at the Newtonian focus of the 122 cm reflector of the Asiago Observatory. On the plate, the scale perpendicular to the dispersion is 127 arc s mm⁻¹. The spectral region around H_α was recorded at a dispersion of 125 Å mm⁻¹. The slit was set 6 arc s wide on the sky, corresponding to 0.35 kpc on the galaxy placed at a distance of 12 Mpc. This gives the best compromise between resolution and speed for our spectrograph. It was centered by eye on the galaxy and the spectrum was taken using an off-set guide star. Other data on the spectrographic material are summarized in Table 3. All the spectra show emission lines of H_α and [N II] λ 6584, [S II] $\lambda\lambda$ 6717–6731 in the long exposure spectra and strong continuum in the position of the nucleus. In all the spectra the line widths are comparable with the instrumental profile.

The spectra were calibrated and the relative emission line intensities of H_α and [N II] λ 6584 were measured in five good quality spectra. Details of the standard reduction technique are described in Benvenuti et al. (1975c). Owing to the distance of the galaxy, no individual H II regions have been resolved with our spectrograph. The only significant data are therefore those relative to the nucleus and to a region extending to the NE at a mean distance of 25'' from the center. For the region outside the nucleus we obtain a mean value for $I(6584)/I(H_\alpha) = 0.41$ which lies between the typical values of the innermost H II regions in spiral galaxies (Searle, 1971) and those of the interarm regions in M 33 (Benvenuti et al., 1976). The $I(6584)/I(H_\alpha)$ ratio in the nuclear region (13'' $\times$ 16'') is 1.03. High resolution radio observations of the nuclear region are strongly recommended in order to check if this relatively

Table 4. Heliocentric radial velocities [km s^{-1}]

Distance from center [arc — sec]	P.A. 30°–33°5						P.A. 10°			
	S 1754		S 1771		S 1852		S 2124		S 1825	S 2170
	H $_{\alpha}$	[N II]	H $_{\alpha}$	[N II]	H $_{\alpha}$	[N II]	H $_{\alpha}$	[N II]	H $_{\alpha}$	H $_{\alpha}$
NE –68.6			638							
–66.0			644				623			
–63.5			646				624			
–61.0			675				618			
–58.4			658				607			
–55.9			669				625			
–53.3			675				611			
–50.8			678				608			
–48.3			658				606			
–45.7			652				620			
–43.2			672				632			
–40.6			672				633			
–38.1			681				619			
–35.6			692				633			
–33.0			706				654			
–30.5			686				654			
–27.9	665		664		650		660			
–25.4	688		698	723	675		655			
–22.9	692		681	740	695	686	679			
–20.3	705	697	695	743	708	697	681	682		
–17.8	706	705	703	718	725	735	708	722	702	695
–15.2	715	715	732	735	735	742	717	740	720	705
–12.7	743	738	734	746	754	740	740	723	727	733
–10.2	739	754	718	780	762	762	761	746	745	743
–7.6	755	765	763	774	771	742	775	758	756	771
–5.1	769	768	788	763	800	770	787	781	770	764
–2.5	796	775	799	785	792	794	799	799	789	789
0.0	808	792	811	794	798	823	837	814	809	806
2.5	809	814	805	816	819	861	860	814	822	808
5.1	805		825	822	819	883	846	800	829	841
7.6			853	814	838		884			869
10.2			889	853	876		864			
12.7			881	873	885					
15.2			920	884	904					
17.8			923	878	876					
20.3			915							
22.9			926							
25.4			932							
27.9			974							
SW 30.5			997							

high ratio is associated with a non-thermal radio source as suggested by Alloin et al. (1976).

The radial velocities were determined from the emission lines following the procedure described by Benvenuti et al. (1975a). The heliocentric recession velocity of the nucleus of NGC 660 was derived from a weighted average of the velocities in the nuclear region. We obtain $V_0 = 805 \pm 20 \text{ km s}^{-1}$ in satisfactory agreement with the 21-cm velocity $V_0 = 854 \text{ km s}^{-1}$ given by Tully (1975, private communication). Correcting this value for a galactic rotation of 300 km s^{-1} toward the Solar Apex ($L^I = 55^\circ$, $B^I = 0^\circ$), and assuming $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the Hubble constant we obtain a distance of 12 Mpc for NGC 660.

IV. Velocity Field

Table 4 contains the heliocentric radial velocities measured from the spectra obtained at P.A. 30°–33°5 and from the two spectra at P.A. 10°. In the former case H $_{\alpha}$ and [N II] emissions were measured, in the latter only the H $_{\alpha}$ line was used. Figure 5 shows the radial velocities as a function of the distance from the center. The curve, relative to the P.A. 30°–33°5, i.e. to the apparent equatorial plane as sketched in Figure 2, contains a fairly symmetric linear part extending up to 32" from the center. This extension is comparable with the dimension of the bar-like structure. The velocity difference between the extremes of the curve is 300 km s^{-1} , again in good agreement with the 21-cm

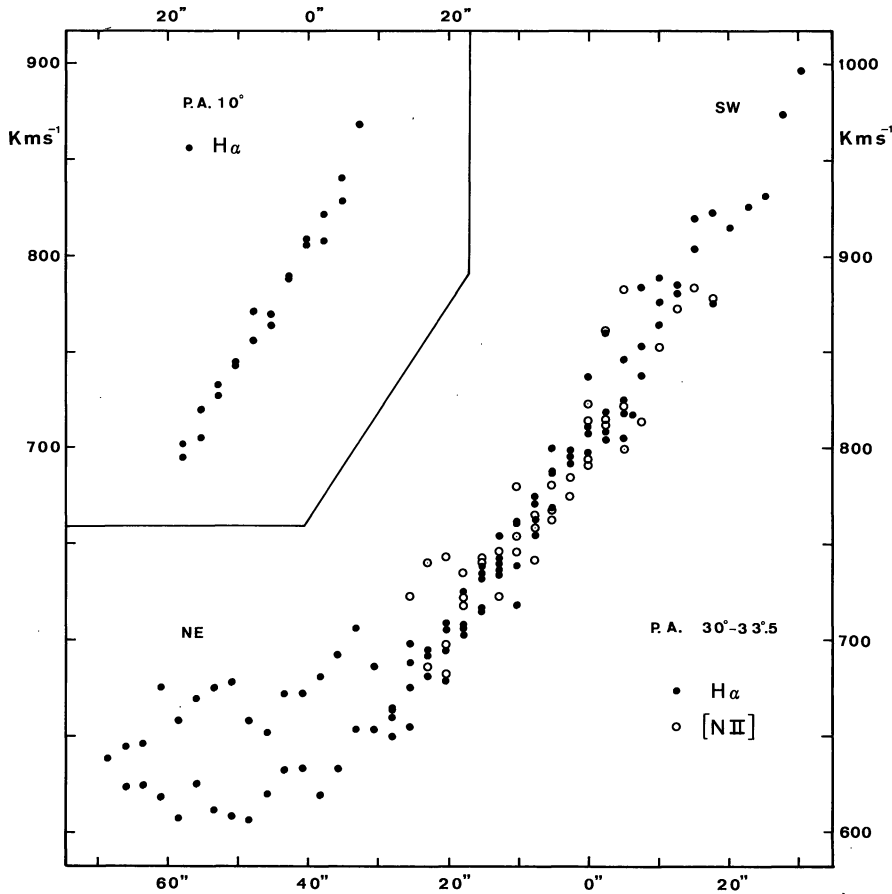


Fig. 5. NGC 660. Observed heliocentric radial velocities at P.A. 30°–33°5 and 10° as a function of the distance from the center

line width at half intensity, 309 km s^{-1} , given by Tully (1975, private communication). In this central part the $\text{H}\alpha$ and $[\text{N II}]$ measures fit very well together with a slope of $5.4 \text{ km s}^{-1} \text{ arc s}^{-1}$.

The emission extends further in the NE direction than toward the SW and the velocity curve correspondingly shows a plateau extending up to $73''$ from the nucleus. The interpretation of this feature as a turning point is uncertain because these measures come from the high-absorption region at the NE end of the bar.

The curve relative to P.A. 10° can also be fitted with a well defined straight line with a slope of $6.3 \text{ km s}^{-1} \text{ arc s}^{-1}$. In this case only $\text{H}\alpha$ measures were retained.

The increase of the observed velocity slope from the P.A. 30° – $33^\circ.5$ to the P.A. 10° indicates that the orientation of the kinematical line of nodes does not coincide with the P.A. 41° of the major axis as defined by the inner isophotes of Figure 3, or with the P.A. 32° of the apparent equatorial plane assumed to be coincident with the principal dust lane (see Fig. 2). The discrepancy could be due to a composite rotation around both the minor axes, as suggested in Section 2, or to the presence of radial motions.

Another explanation is that the line of nodes that we have derived from the isophotes of the bar is not correct because the heavy absorption and the complex morphology of the outer regions are hiding the true geometry of the galaxy.

More spectra with greater dispersion, improved resolution and at different position angles would be necessary to discriminate between the three hypotheses by means of a kinematical analysis. However, the low surface brightness of the galaxy outside the bar makes it very difficult to obtain such velocity information. In a spectrum at P.A. 123° , corresponding to the direction of the minor axis of the bar, no emission was detected outside the nuclear region.

Due to this unresolved uncertainty it is not possible to derive a final rotation curve and the relative mass distribution, and we can give only an estimate of the mass of the inner part.

Assuming that the mass is distributed uniformly within a single spheroid of semimajor axis a and axial ratio c/a , the mass is determined by:

$$M = \frac{a\omega^2}{\alpha G}$$

where:

$$\alpha = \frac{3}{2} \frac{1}{a^2 - c^2} \left[\frac{a}{(a^2 - c^2)^{1/2}} \cos^{-1} \left(\frac{c}{a} \right) - \frac{c}{a} \right]$$

and ω is the slope ω_0 of the rotational curve corrected for the tilt effect:

$$\omega = \omega_0 \operatorname{cosec} i.$$

Assuming tentatively an inclination $i=63^\circ$ from the axial ratio $a/b=0.46$ (see Sect. II), and P.A. $=32^\circ$ for the major axis defined by the absorbing lane that crosses the main body, we obtain $a=30''=1.75$ kpc and $\omega=104.3$ km s $^{-1}$ kpc $^{-1}$. The ratio c/a is not determinable from observation, but using $c/a=1/10$ and $c/a=1/3$ as extreme values, the mass ranges between $6.5 \cdot 10^9 M_\odot$ and $8.2 \cdot 10^9 M_\odot$. Corresponding mass-to-light ratios, obtained by integration of the equivalent luminosity profile up to $r^*=a \times (b/a)^{1/2}=20''$, result 9.3 and 11.7 respectively.

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