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NGC 6240: A unique interacting galaxy

J. W. Fried and H. Schulz

Max-Planck-Institut für Astronomie, Königstuhl, D-6900 Heidelberg, Federal Republic of Germany

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Summary. A pronounced double nucleus has been detected on an S 1 image tube plate in the I band and on r and I exposures taken with a CCD camera. Image tube spectrograms provide evidence that the extended regions of ionized gas in this object are dominated by shock heating on a scale of about 6 kpc. We interpret the two components of the nucleus as the remnant nuclei of two galaxies in the process of merging.

Key words: galaxies – interacting galaxies – active galaxies – radio galaxies

1. Introduction

The radio galaxy NGC 6240 (=IC 4625=UGC 10592=MCG 00-43-004=VV 617=4C 2.44=Pks 1650+024) is remarkable by virtue of its chaotic morphological appearance. On Palomar Sky Survey prints it has an asymmetric form and two appendages. A faint nebulosity of about the same size as the bright part of the object extends north-east of the galaxy.

Zwicky et al. (1961) remarked that "multiple collisions" might be responsible for its appearance. Vorontsov-Vel'yaminov (1977) regarded this galaxy as belonging to the class "nests and possible nests of galaxies" and noted "three objects". Although large scale plates by Fosbury and Wall (1979, hereafter FW) and Zasov and Karachentsev (1979) show many more details than the POSS, the plates do not reveal the existence of separate components. In this paper we actually demonstrate that the nucleus of NGC 6240 consists of two components.

Whereas all authors agree that this object is probably an interacting galaxy its spectroscopic classification is still under debate. Arkhipova and Esipov (1979) as well as Zasov and Karachentsev (1979) considered it to be a strongly reddened Seyfert galaxy. FW, on the other hand proposed that the nuclear spectrum results from shocks which are produced by cloud-cloud collisions of the merging galaxies. The spectroscopic observations presented here provide some support for the suggestion of FW.

2. Direct imaging

We obtained large scale exposures on several occasions on Calar Alto Observatory, Spain. The first observations were made in June 1980 with the 2.2 m-telescope (11".7 mm^{-1}) and an RCA C33020C S 1-image tube (Beetz et al., 1974) in the Johnson R and I bands. Exposure times were 45 and 15 min, respectively. A second pair of plates was made in August 1980 with a Varo 8605-1 one stage image tube attached to the Cassegrain focus of the 1.2 m-telescope (21".0 mm^{-1}). Exposure times were 10 min in unfiltered light (extended red cathode, 4000–9000 Å) and 2 hours with an interference filter centered on redshifted H_α (6723±85 Å).

A preliminary discussion of these observations has been given as a conference report (Fried and Schulz, 1982). The main result was the detection of the double nucleus which appears to be most prominent in the I-band and on the S-20 plates. In H_α light the nuclear region is embedded in a bright 3-pointed structure (cf. FW) of 14" extent.

Further observations were made in March 1982 with a CCD camera attached to the 2.2 m-telescope. This camera uses an RCA chip with 320×512 pixels, each 30 μm = 0".34 square, thus covering 2'×3' on the sky. Two frames were obtained: a 10 min exposure in the I-band (defined by a Schott RG 830 filter) and a 5 min exposure in the r-band (Thuan and Gunn, 1976). These two frames clearly show the double nucleus (Fig. 1).

Because of its larger field (diameter 7'.8 compared to 2'×3' for the CCD) we used the S 1 I-plate to derive the coordinates of the nuclei. They were measured relative to 13 reference stars, the positions of which were determined on the POSS blue glass plate relative to SAO stars. The internal accuracy of the fit is about 1".5. We obtained for the 1950.0 equinox:

Nucleus I: $\alpha = 16^h50^m27^s.96$ $\delta = 2°28'55''.2$

Nucleus II: $\alpha = 16^h50^m27^s.98$ $\delta = 2°28'57''.0$.

The two nuclei are thus oriented at a position angle of 10° and separated by 1".8. The diameters, estimated from the S 1 I-plate, are 2".5 and 1".5 for nuclei I and II, respectively. Both nuclei appear to be non-stellar so that an accidental projection of a foreground star is ruled out.

Photometric measures have been derived from the CCD exposures (Table 1). BD+54°1216 and BD+25°1981 (Thuan and Gunn, 1976) were used as photometric standard stars for the r, and the star 105–214 in the list of Moffet and Barnes (1979) for the I-band. Coefficients typical for Calar Alto were applied to correct for atmospheric extinction. The accuracy of the data is about 0.2 mag.

The color index $(r-I)$ of the total galaxy indicates reddening compared to typical E or S galaxies for which $(R-I) \approx 0.8...0.9$ (Johnson, 1966). This reddening is due to galactic foreground extinction. For the stars HD 148743, 149277, 149363, 154445, and

Send offprint requests to: J. W. Fried

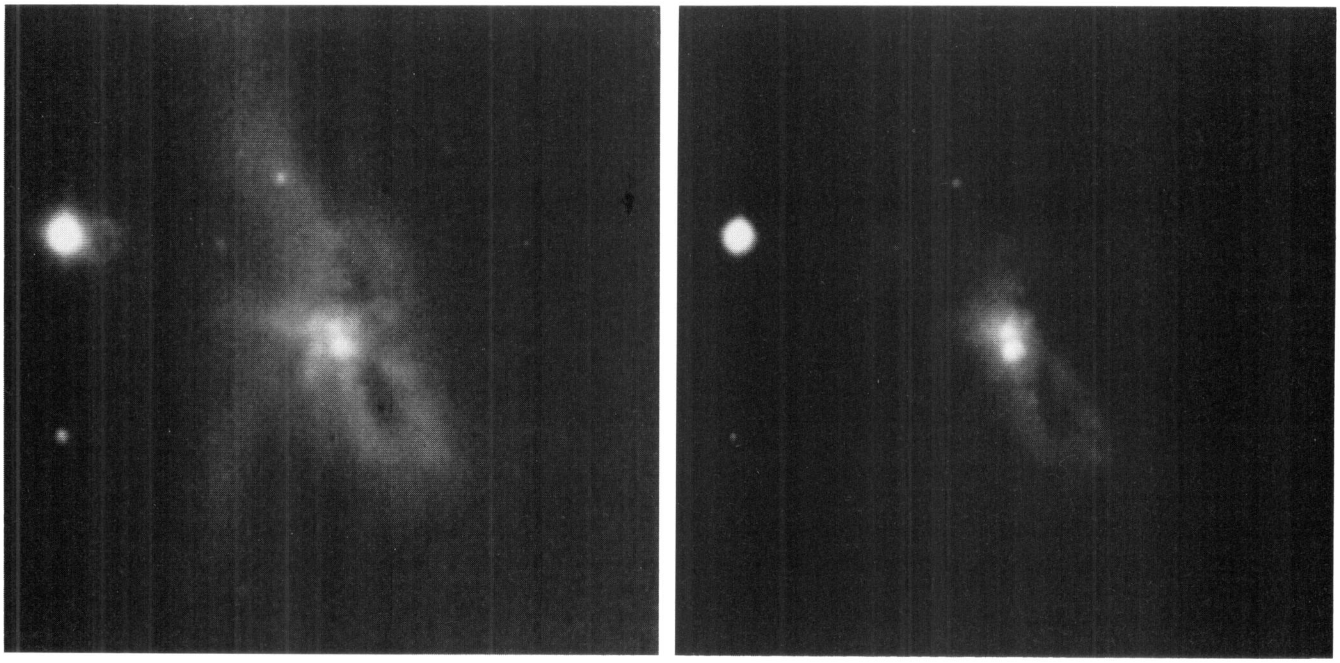

Fig. 1. CCD exposures of NGC 6240. *N* is on the top, *E* to the left. Left: *r*-band, 5 min. Right: *I*-band, 15 min

Table 1. CCD Photometry

	Aperture	r	$(r-I)$	M_r	M_r^0
Nucleus I	$2''.4 \times 2''.4$	16.1	1.7	−18.2	−22.2
Nucleus II	$1''.6 \times 1''.6$	17.1	1.7	−17.2	−21.2
NGC 6240	$70'' \times 41''$	12.6	1.2	−21.7	−22.7

M_r = absolute r-magnitude ($H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
M_r^0 = absolute r-magnitude corrected for extinction (cf. text)

156247 – which are all located within 5° from NGC 6240 – we obtain from the values given by Neckel et al. (1980) a mean $A_v = 0.94$, in close agreement with Arkhipova and Esipov (1979) who had obtained $A_v = 1$ mag. For a typical extinction law $E(r-I) = 0.32\,A_v$; therefore, the dereddened color index $(r-I)_0 = 0.98$ is close to typical values.

The two nuclei appear to be extremely faint compared to the total galaxy. In the r-band the radiation emitted by the nuclei is only 6% of the total emission. This is evidently caused by strong internal extinction in the galaxy itself. The direct plates (cf. Plates 1 and 2 in FW) show large amounts of dust. Using the Balmer decrement FW had obtained $A_v = 4 \pm 0.5$ mag for the central $3'' \times 6''$. Correcting for extinction with $A_v = 1$ mag for the whole object and $A_v = 4$ mag for the nuclei, we obtain $r = 13.1$, 14.1, 11.9 for nucleus I and II and the whole object, respectively. The nuclei are intrinsically as bright as Seyfert nuclei (cf. M_r^0 in Table 1), though NGC 6240 is not a Sy galaxy by virtue of its spectrum.

The dereddened color indices of the 2 nuclei are $(r-I)_0 = 0.4$ (with $A_v = 4$ mag), indicating colors bluer than typically found. However, these colors are affected by the strong emission lines contained in the r-filter band.

NGC 6240 also appears on archival plates of the Landessternwarte Heidelberg. The object is barely visible on the 6 twin exposures which were made with the Bruce double astrograph ($0^{\mathrm{m}}.4$ aperture) on blue sensitive plates between 1901 and 1962. Interestingly, the two plates taken on 1927 June 1 show a nucleus-like feature. Since the quality of these plates is not superior to that of the other plates, the enhanced emission may be due to activity in the object's nucleus. However, the detection is only marginal and we recommend that NGC 6240 should be inspected in other archival plate collections.

3. Spectroscopic observations

Four spectra of the galaxy with different slit positions have been obtained with the Cassegrain spectrograph at the 2.2 m-telescope between March 12 and 15, 1980. An ITT F 4089 two-stage image tube and IIa-O plates were employed as detector. The spectrograms cover the wavelength range from 5200 to 7000 Å at a resolution of 3–4 Å (reciprocal dispersion 60 Å mm^{-1}). Typical exposure times were 30 min. All spectra were intensity calibrated by means of a Lyot filter element (Trefzger and Solf, 1978). The spectra were scanned in strips parallel to the direction of dispersion with the Grant machine at MPI-A with a scanning aperture corresponding to $5''.5 \times 1.25$ Å. Apertures projected on the sky of those scans from which we derived radial velocities are shown in Fig. 2. The night sky spectrum was scanned on the outermost parts of each plate and subtracted from the galaxy spectra of the same plate. The emission lines of [O I] $\lambda\lambda$ 6300, 6364, [S II] $\lambda\lambda$ 6716, 6731, [N II] $\lambda\lambda$ 6548, 6583 and H_α are unambiguously identifiable in most of the spectra. Unfortunately, the redshifted [O I] and [S II] lines are close to night sky emission lines. Since errors in the night sky subtraction propagate much stronger in line positions than in line strengths, the derivation of radial velocities and line widths was restricted to H_α and the [N II] lines.

Line strengths and positions for the H_α+[N II] blend were obtained from fits of three Gaussian components and a linear continuum. The line positions were corrected for distortion of the image tube by using the [O I] $\lambda\lambda$ 6300, 6364 and OH λ 6864 night

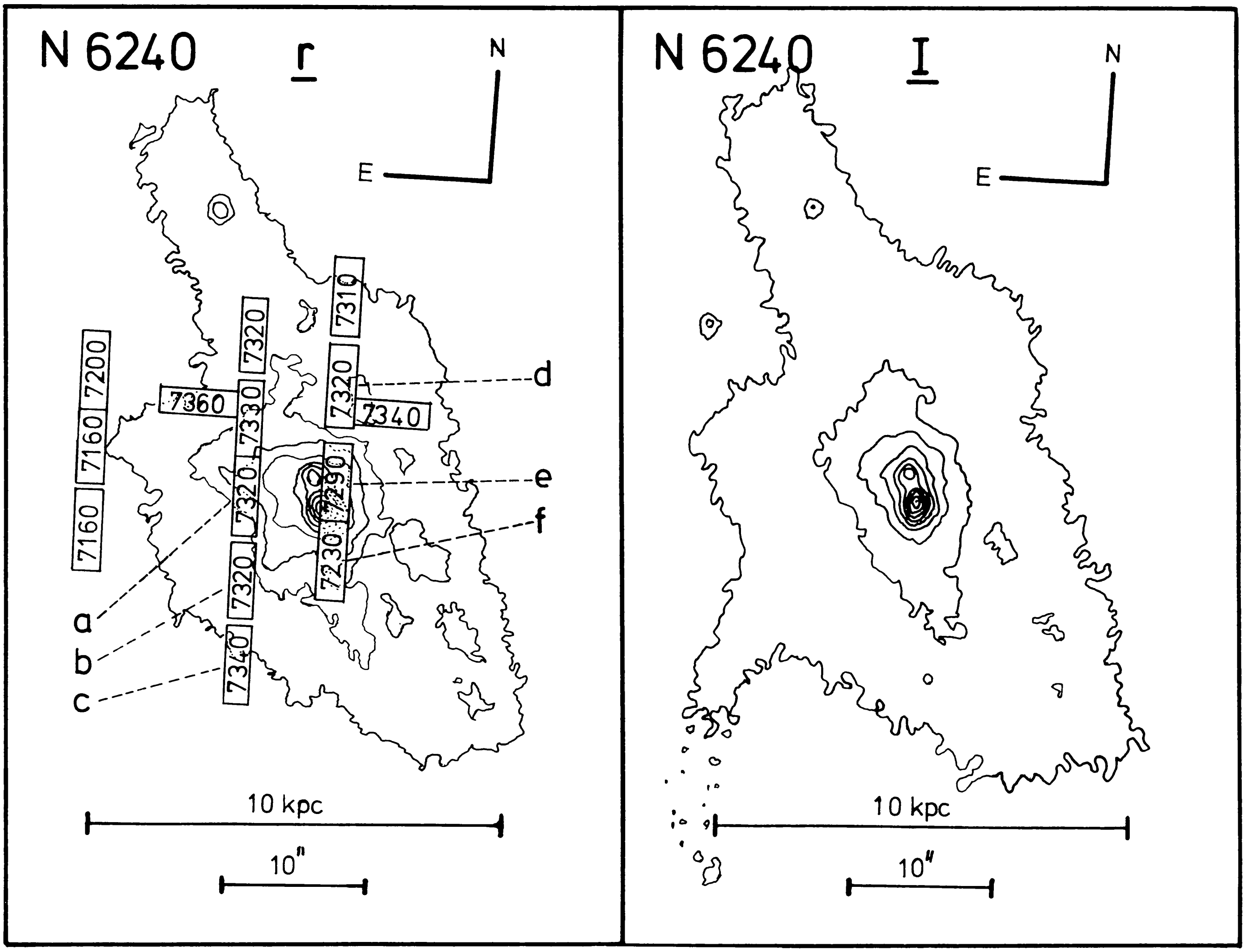

Fig. 2. Isophote-plots of the CCD-exposures of Fig. 1. Left: r-band. The numbers in the rectangles are the measured heliocentric velocities, the letters $a-f$ mark the positions of the spectra shown in Fig. 3. Right: I-band

sky lines. These corrections are of the order of $30\,\mathrm{km\,s^{-1}}$. Line strengths for the [O I] and [S II] lines were obtained from fits of one or two Gauss components and a linear continuum. Examples of sky-subtracted tracings are shown in Fig. 3. The peaks of H_α and [N II] $\lambda\lambda 6583$ are clearly separated which facilitated the deconvolution. The most conspicuous characteristic of the spectra is that the [O I], [N II], and [S II] lines are far stronger relative to H_α than in normal H II regions.

From the spectra $a-e$ shown in Fig. 3 we measured the following mean line ratios ($\pm\sigma$ of the sample): [O I] $\lambda 6300/H_\alpha = 0.5 \pm 0.13$, [N II] $\lambda 6583/H_\alpha = 1.5 \pm 0.35$, and [S II] $\lambda\lambda 6716, 6731/H_\alpha = 1 \pm 0.2$. These values are not typical for photoionization involving hot stars and normal elemental abundances. We used these ratios together with the extinction corrected line intensities of FW (note: H_α and the [N II] lines are *not* resolved in FW's spectrum) to form those combinations of line ratios which can be used to discriminate between different excitation mechanisms with the diagrams of Baldwin et al. (1981). In all cases NGC 6240 appears in regions of the diagrams which are only occupied by shock excited objects. Using the diagnostic diagrams of Dopita (1977) we derive a preshock total gas density of $10^2\,\mathrm{cm^{-3}}$ and a postshock temperature of $8\,10^4$ K. The similarity of the line ratios in regions which are at least up to 6 kpc apart shows that shock heating prevails on a surprisingly large scale in this galaxy. In the outermost regions only [N II] $\lambda 6583/H_\alpha$ is measurable; it appears to be still high (between 1 and 2) in the northern regions whereas just south of the double nucleus H_α starts to dominate (Fig. 3f).

Heliocentric radial velocities are given in Fig. 2. These are derived from the Gaussian fits to the [N II] $\lambda 6583$ and H_α lines. As estimated from the fits, the errors of the velocities are typically 20–30 $\mathrm{km\,s^{-1}}$. Most velocities are close to $7320\,\mathrm{km\,s^{-1}}$, in good agreement with the radial velocity of $7340\,\mathrm{km\,s^{-1}}$ obtained by Zasov and Karachentsev (1979). FW had obtained $7362\,\mathrm{km\,s^{-1}}$ for the Na I absorption, but $7550\,\mathrm{km\,s^{-1}}$ for the emission lines. The difference of $130\,\mathrm{km\,s^{-1}}$ might be due to a high-velocity component not covered by our slit positions.

Strong deviations from the average velocity have been found only in the east (Fig. 2) from very faint H_α and [N II] $\lambda 6583$. The region close to the double nucleus appears slightly blueshifted (e and f in Fig. 2) and there is some evidence that the blueshifts increase south of spectrum f. We conclude that large scale velocity variations of the order of $100\,\mathrm{km\,s^{-1}}$ exist. There is, however, no clear-cut pattern in the variations.

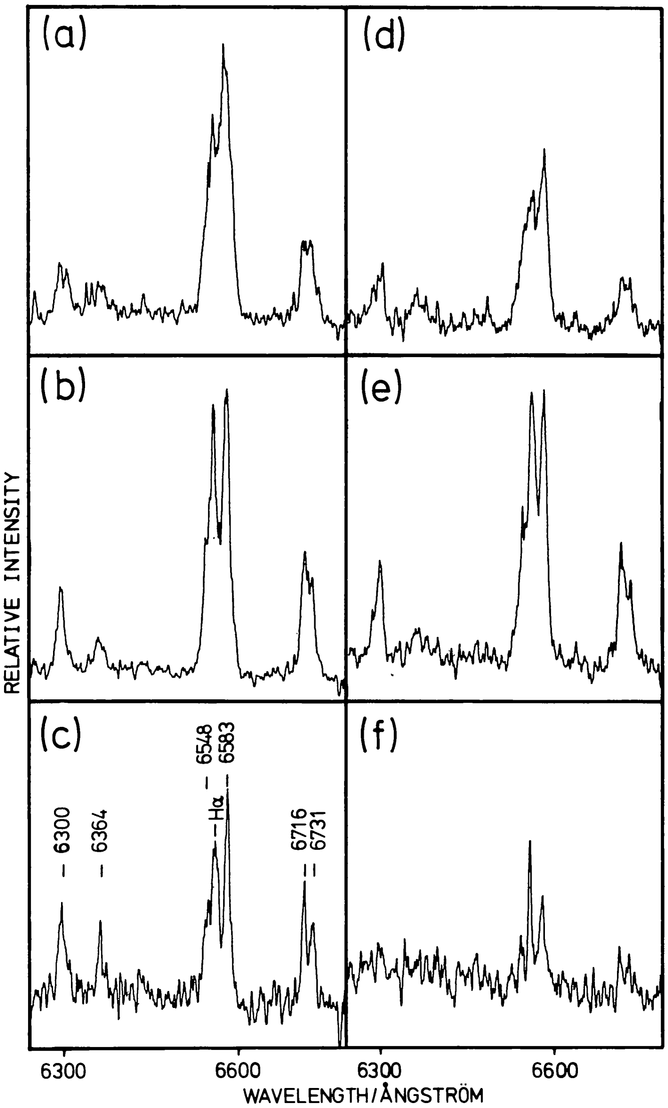

Fig. 3. Spectra of NGC 6240. The slit positions are marked by corresponding letters in Fig. 2

Unfortunately our slit positions do not cover the nuclei. The reason is that the spectra were taken before the detection of the double nucleus, and an attempt to take spectra of the nuclei was hampered by bad weather conditions. Due to the small separation of the two nuclei of 1''8 excellent seeing conditions are required for such observations.

From comparison of the widths of the Gaussian profiles fitted to the $H_\alpha+[\text{N II}]$ emission lines and airglow lines we derive turbulence velocities v_t (defined by assuming a Gaussian velocity distribution of the form $\exp(-v^2/v_t^2)$; note that FWHM $=1.67\,v_t$) between 150 and 350 km s^{-1} with a median value of 220 km s^{-1}. Given the size of the apertures of 2 kpc × 0.7 kpc (for $H_0=100$ km s^{-1} Mpc^{-1}) NGC 6240 shows velocity differences of some hundred km s^{-1} on scales of 1 kpc!

4. Discussion

The disturbed morphology of NGC 6240 (cf. Fig. 1) clearly shows that this galaxy is very unusual. Intuitively, the double nucleus and the tails might be due to explosive event(s) or to collision(s). However, morphological similarities to the results of the model computations of Toomre and Toomre (1972) lead us to interpret NGC 6240 as a collision of two galaxies, the nuclei of which are shown on our *r* and *I* exposures. FW had obtained plates which did *not* show two distinguishable galaxies. Therefore they concluded that the galaxies had already merged by the process of dynamical friction. Evidently this is not the case.

The computer simulations of Toomre and Toomre (1972) show that the masses of the interacting galaxies must not be too different if tails are to be formed. Unless the mass to light ratio of the two nuclei differs very much and/or the absorption in front of the nuclei, our photometric data show that the nuclei of the two colliding galaxies are of comparable mass. This supports the interpretation of NGC 6240 as a collision.

A VLA radio map at 4885 MHz has recently been published by Condon et al. (1982) which also shows the double nucleus. The radio and our near infrared position agree within one sigma, while the relative positions of the two nuclei agree to about 0''1. Even the brightness ratios of the two nuclei are similar although the radio emission is definitely nonthermal in contrast to the optical radiation.

Condon et al. explain the radio emission in their sample of bright spirals by synchrotron radiation from supernova remnants which have been produced after bursts of star formation. They propose that these bursts were triggered by strong galaxy-galaxy interactions. Both the coincidence of the optical and near infrared structure with the radio map and the evidence that we are just seeing a "hard" collision of two galaxies support this picture for NGC 6240.

The star burst model can be further tested by comparing the ratio of the optical to the radio flux as has been recently shown by Ulvestad (1982). The radio flux density of NGC 6240 is 80 mJy at 4885 MHz (Condon et al., 1982) and we derive a total *V*-flux of the two nuclei of 33 mJy (assuming $A_v=4^{\rm m}$ and $V-r=0.9$). The respective numbers for the Seyfert galaxy NGC 7469 are 65 and 22 mJy. Ulvestad rejected a star burst model for this latter object since it would predict a 67 times larger *V*-flux than observed. The ratio visual to radio flux is on the same order for NGC 6240 and therefore the star burst hypothesis is invalidated unless the conditions in NGC 6240 are extremely different from the model assumptions. It should also be pointed out that our spectra do not show line ratios which are typical for gas being photoionized by hot stars as would be expected from a simple star burst model.

A still viable alternative to the burst model is the suggestion of FW that both the optical and radio emission are essentially caused by the shocks from cloud-cloud collisions.

In summary we conclude that NGC 6240 has very unusual properties: the galaxy has two strongly reddened nuclei which are only 1''8 = 640 pc (projected on the sky) apart and the line spectra show strong signs of shock excitation on the rather large scale of 6 kpc. To our knowledge, these are unprecendented results for an interacting galaxy (cf. Borchkhadse and West, 1980; Bergvall et al., 1981). Therefore we regard NGC 6240 as a "unique" object which clearly deserves more detailed investigations.

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