THE OPTICAL COUNTERPART OF THE RADIO SOURCE CLOSE TO THE SEYFERT 2 NUCLEUS OF NGC 5953≡ARP 91 B^{a)}

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ABSTRACT

Spectroscopic and morphological observations of the nuclear region of the Seyfert 2 galaxy NGC 5953≡Arp 91 B are presented. It is shown that an extended emitting region, with features typical of a supergiant H II region, is located to the west of the nucleus within a radio structure which is emitting as a nonthermal source with spectral index $\alpha = 0.6$ in the 1.4–5.0 GHz range. The faintness of the [O III] $\lambda\lambda$ 4959, 5007 emission lines in the spectrum of this region is discussed in terms of a state of low ionization, and high abundances of heavy elements in the emitting gas. In addition, the possibility that the ionization is produced by the Seyfert 2 nucleus and that its luminosity has undergone an abrupt decrease in luminosity has been taken into account. The nonthermal radio emission is tentatively interpreted as the result of frequent supernova blasts and the consistency of this interpretation with the optical data is discussed. Another extended emitting region, located close to the nucleus to its east, in a position symmetrically opposite to the western region, is revealed by our spectra. Its line ratios and fluxes are typical of a very luminous giant H II region. A bright stellar “knot,” located 3″ west of the nucleus, just within the emitting region associated with the extended radio source, is a foreground star of spectral type F8-G2 and magnitude $V \sim 16$.

I. INTRODUCTION

NGC 5953/4 (Arp 91 A/B, VV 244 A/B) is a close interacting pair of galaxies consisting of a Seyfert 2 component NGC 5953 (Keel *et al.* 1985), classed as S0 Nilson (1973), and as Sa by de Vaucouleur, de Vaucouleur, and Corwin (1976); and a distorted spiral component, NGC 5954, located 43″ to the northeast (position angle 30°) of NGC 5953, characterized by the presence of a few luminous H II complexes, including one of low ionization at the nucleus (Keel *et al.* 1985).

A radio source, coincident with the optical centroid of NGC 5953/4, was detected at 2.7 and 5.0 GHz by Wright (1974). Further radio flux measurements at 2.4 GHz, performed by Dressel and Corwin (1978), using higher angular resolution, showed that both galaxies are radio sources, the stronger one being NGC 5953. Infrared observations of the system in the range 12–100 μm from *IRAS* and in the range 1.25–10 μm from the ground (Cutri and McAlary 1985) revealed that NGC 5953 is a strong infrared source of increased intensity up to 100 μm . Conversely, NGC 5954 does not show any sign of emission beyond 10 μm .

Recently Jenkins (1984) collected near-UV, optical, and radio data attempted to explain the morphological and spectroscopic features of the NGC 5953/4 pair in terms of star formation triggered by their close interaction. Jenkins found that the nucleus of NGC 5953 is distorted into a pear shape in both H α and visual images, and that a double radio structure, identified in the 5.0 and 1.4 GHz maps, is located within this region. The separation of the two radio components, $\sim 5''$, and their P.A., $\sim 90^\circ$, correspond in a first approximation to the length and orientation of the major axis of the optical pear-shaped nucleus. Moreover, Jenkins found that the radio-continuum distribution of NGC 5953 from 408

MHz to 5.0 GHz is a power law with spectral index $\alpha = 0.65$, typical of supernova remnants (Clark and Caswell 1976).

In this paper we present optical imaging and spectroscopy of the nuclear region of NGC 5953. Our data show that the east–west pear-shaped nuclear bulge is resolved into two “stellar” components, resulting from the fortuitous alignment of a faint foreground star with the radio source located close to the nucleus to its west. In addition, two extended emitting regions have been identified. One overlaps to the radio structure to the west of the nucleus and shows features typical of a bright heavy-element-rich H II region of low degree of ionization. The other region is located to the east of the nucleus.

II. OBSERVATIONS AND REDUCTIONS

Our data were obtained with the CCD spectrograph at the Cassegrain focus of the Shane 3 m telescope of the Lick Observatory using both the grism and the UV mode (Lauer *et al.* 1984; Miller and Stone 1987).

Two long-slit spectra were taken in the UV mode, using 300 lines/mm gratings blazed at $\lambda = 4230 \text{ \AA}$ and $\lambda = 7500 \text{ \AA}$, respectively and a 2″ wide slit oriented east–west. Both spectra were taken with a Texas Instruments 800×800 three-phase CCD with a pixel size of 15 μm and cover the spectral regions $\lambda\lambda$ 3600–6750 $\text{\AA}$ and $\lambda\lambda$ 6600–9700 $\text{\AA}$, respectively. The typical resolution, full width at half maximum (FWHM) of a faint comparison line, is $\sim 13 \text{ \AA}$ and the scale along the slit is 0.66″/pixel. One long-slit spectrum was also taken in the grism mode using the same setup of the slit and a 600 lines/mm grism blazed at $\lambda = 6500 \text{ \AA}$. The spectrum covers the spectral region $\lambda\lambda$ 5800–7600 $\text{\AA}$ and has a typical mean resolution of $\sim 9 \text{ \AA}$. The scale along the slit is 0.71″/pixel. The spectra were calibrated, reduced, and measured by essentially the same procedures described by Osterbrock and De Robertis (1985). The VISTA image-processing package developed at Lick Observatory and the spectral

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analysis program RETICENT (Pritchet, Mochnacki, and Yang 1982) were used.

One narrow-band interference filter image of NGC 5953/4 in continuum light was taken using the Cassegrain spectrograph in the direct-imaging mode, scale $0.71''/\text{pixel}$. The narrow-band filter used had a bandpass of $\sim 100 \text{ \AA}$ and central wavelength $\lambda_c = 6107 \text{ \AA}$. The image was divided by the appropriate flat field using the twilight sky, and an estimate of the background sky level was subtracted.

III. DISCUSSION

a) Description and Redshifts

As shown by the direct image in Fig. 1, the central part of NGC 5953 is separated into two "point sources," a Seyfert 2 nucleus *A* and a knot at a distance of $3''$ to its west. The contour map of the $H\alpha$ and $[\text{N II}]$ lines in Fig. 2 shows that the knot seems to be associated with an emitting region *B*, which extends up to a distance of $\sim 8.5''$ west of the nucleus and has a diameter of $\sim 7.5''$. An extended emitting region *C* with the same diameter of *B* is present to the east of the Seyfert 2 nucleus. The heliocentric redshifts of *A* and *B*, derived from the $H\alpha$, $[\text{N II}]$, and $[\text{S II}]$ lines on the higher dispersion Lick spectra are $z(A) = z(B) = 0.0070 \pm 0.0001$.

Conversely, the redshift of the *C* source, derived in the same way, is slightly but significantly smaller $z(C) = 0.00670 \pm 0.00004$. These redshift values correspond to distances $d(A) = d(B) = 21 h^{-1} \text{ Mpc}$, and $d(C) = 20 h^{-1} \text{ Mpc}$ evaluated taking for the Hubble constant the value $H = h \times 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The scales at those distances are $s(A) = s(B) = 102 h^{-1} \text{ pc arcsec}^{-1}$, $s(C) = 97 h^{-1} \text{ pc arcsec}^{-1}$, respectively. The spectrum of the knot is composite, being characterized by emission lines having the same redshift of *B* and by absorption lines and absorption bands with radial velocity $v = -9 \pm 35 \text{ km s}^{-1}$, typical of a star of spectral type F8-G2. The absorption spectrum was classified after subtraction of the residual emission from the underlying galaxy, which was estimated from a

FIG. 1. CCD image of NGC 5953/4 in continuum radiation at $\lambda \sim 6100 \text{ \AA}$. The image orientation is north up, east to the left.

FIG. 2. Contour map of $H\alpha$ and $[\text{N II}]$ lines. East is to the left.

profile of $H\alpha$ along the slit. The absence of redshift and the "point source" shape of the knot argue that its observed spectrum is a combination of the spectrum of a foreground star and the spectrum of the underlying emitting region *B* associated with the galaxy. We can thus conclude that the knot is a foreground star and that its accidental close alignment with the nucleus of NGC 5953 is likely to have produced the pear-shaped distortion observed by Jenkins (1984).

b) Emission-Line Regions

The spectra of the components *A*, *B*, and *C* are shown in Fig. 3. The low-dispersion spectrum of *B* has been obtained after subtraction of the spectrum of the foreground star. The relative line intensities and their equivalent widths were measured on the low-dispersion spectra up to $H\alpha$. The $H\alpha$, $[\text{N II}]$ complex and the $[\text{S II}]$ doublet could be separated and measured on the higher dispersion spectra, which are also shown in Fig. 3. The observed emission-line fluxes were corrected for galactic reddening using the extinction values given by Burstein and Heiles (1984) and the Whitford reddening law as parametrized by Miller and Mathews (1972). A further correction was made for internal reddening comparing the relative strength of the Balmer lines $H\alpha:H\beta:H\gamma$ with the AGN Balmer decrement calculated by Ferland and Netzer (1983), $H\alpha:H\beta:H\gamma = 3.1:1.0:0.47$ and with the case *B* recombination decrement calculated by Brocklehurst (1971) $H\alpha:H\beta:H\gamma = 2.85:1.0:0.47$ for $T = 10^4 \text{ K}$ and $N_e = 10^4 \text{ cm}^{-3}$. The equivalent widths and the relative intensities of the emission lines are quoted in Table I. $F(\lambda)/F(H\beta)$ indicates the observed line ratio while $I(\lambda)/I(H\beta)$ is the same line ratio corrected for galactic and internal reddening. The accuracy of the intensities of the strongest lines is estimated to be better than $\pm 20\%$, while the faintest features could have uncertainties as large as a factor 2. The values of the logarithmic internal reddening constant at $H\beta$, $c(H\beta)$ are also quoted in Table I. The intrinsic FWHMs of the emission lines were measured following a procedure similar to that described by Osterbrock and Pogge (1985). The FWHMs of the $[\text{O I}]$, $H\alpha$, $[\text{N II}]$, and $[\text{S II}]$ lines measured in the high-dispersion spectra are significant for the Seyfert 2 nucleus only, since they are typical of the instrumental profile for the *B* and *C* components. Their mean values are listed in Table II together with the average intrinsic FWHM of the nuclear lines.

FIG. 3. CCD spectra of NGC 5953 A = Seyfert 2 nucleus, NGC 5953 B = west component, and NGC 5953 C = east component.

TABLE I. Relative intensities and equivalent widths.

Line	λ	Nucleus A			West Extension B			East Extension C		
		W_λ (Å)	$F_\lambda/F_{H\beta}$	$I_\lambda/I_{H\beta}$	W_λ (Å)	$F_\lambda/F_{H\beta}$	$I_\lambda/I_{H\beta}$	W_λ (Å)	$F_\lambda/F_{H\beta}$	$I_\lambda/I_{H\beta}$
[O II]	3726,29	18.7	4.24	12.77	10.5	1.09	1.65	12.1	2.51	5.68
H γ	4340	0.7	0.22	0.38	2.4 ^a	0.22 ^a	0.27 ^a	1.7	0.32	0.48
[O III]	4363	...	...	...	...	...	...	...	...	...
H β	4861	2.5	1.00	1.00	12.3	1.00	1.00	5.4	1.00	1.00
[O III]	4959	4.9	1.98	1.83	0.7 ^b	0.06 ^b	0.06 ^b	1.1 ^b	0.21 ^b	0.20 ^b
[O III]	5007	12.4	4.98	4.39	2.2	0.18	0.17	3.4	0.63	0.57
[O I]	6300	2.2	1.06	0.33	1.0	0.06	0.04	1.4	0.29	0.12
[O I]	6364	0.7	0.32	0.09	...	...	...	...	...	...
[N II]	6548	7.8	3.90	1.05	8.7	0.57	0.35	5.9	1.29	0.49
H α	6563	20.5	10.38	2.78	72.4	4.73	2.89	35.9	7.91	2.98
[N II]	6583	23.3	11.67	3.09	27.5	1.80	1.09	18.1	4.02	1.50
[S II]	6716	5.4	2.77	0.67	10.5	0.69	0.41	6.7	1.49	0.53
[S II]	6731	5.4	2.77	0.67	8.2	0.54	0.32	5.5	1.22	0.43

a) uncertain value

b) calculated using $I([O III]5007) = 2.95 I([O III]4959)$.Nucleus: $F(H\beta) = 1.05 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ $I(H\beta) = 5.84 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ $c(H\beta) = 1.70$ West knot: $F(H\beta) = 1.91 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ $I(H\beta) = 8.51 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ $c(H\beta) = 0.61$ East extension: $F(H\beta) = 4.97 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ $I(H\beta) = 9.75 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ $c(H\beta) = 1.25$

The spectra of *A*, *B*, and *C* were classified using the diagnostic diagrams proposed by Veilleux and Osterbrock (1987), Fig. 4, which allows distinction between H II region-like objects and narrow line active galactic nuclei (NLAGN). In all diagrams the spectrum of *A* is characterized by line ratios which are typical of NLAGNs, while the spectra of *B* and *C* are characterized by ratios typical of low-ionization H II regions. It is interesting to note the extreme faintness of the [O III] $\lambda\lambda$ 4959, 5007 lines in the spectrum of *B* and the absence of [O III] λ 4363 in the spectra of *A*, *B*, and *C*. The weakness of [O III] λ 4363 corresponds in the low-density limit to temperatures lower than $T_e = 10^4$ K. Assuming $T_e = 10^4$ K in *A*, *B*, and *C* the [S II] 6716/6731 ratios correspond to electron densities $N_e(A) \sim 1200 \text{ cm}^{-3}$, $N_e(B) \sim 300 \text{ cm}^{-3}$, and $N_e(C) \sim 500 \text{ cm}^{-3}$. The H β luminosities $L(H\beta) = L_{100} h^{-2}$, where L_{100} is the H β luminosity

for $H = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ corrected for internal reddening, $L(H\beta) \sim 4.5 \times 10^{39} h^{-2} \text{ ergs s}^{-1}$ in *B*, $L(H\beta) \sim 5.1 \times 10^{39} h^{-2} \text{ ergs s}^{-1}$ in *C*, are of the same order of magnitude as the nuclear H β luminosity $L(H\beta) \sim 3.1 \times 10^{40} h^{-2} \text{ ergs s}^{-1}$. These values correspond to a number of photons being consumed to ionize H^0 atoms: $Q(H)_A = 6.5 \times 10^{52} h^{-2} \text{ s}^{-1}$, $Q(H)_B = 9.4 \times 10^{51} h^{-2} \text{ s}^{-1}$, $Q(H)_C = 1.1 \times 10^{52} h^{-2} \text{ s}^{-1}$, respectively. The H β luminosity of the nucleus *A* is comparable with the mean value $L(H\beta) \sim 2.8 \times 10^{40} h^{-2} \text{ ergs s}^{-1}$ typical of Seyfert 2 nuclei (Dibai and Tsvetanov 1980), while the H β luminosities of *B* and *C* are unusually large for galactic H II region-like objects whose H β luminosity (Kennicutt 1984) range from $3.5 \times 10^{36} \text{ ergs s}^{-1}$ in Orion to $7.0 \times 10^{38} \text{ ergs s}^{-1}$ in W49. For comparison purposes we have taken the most luminous H II regions observed by Searle (1971) in M33, M101, M51 and those observed by Heckman and Balick (1980) in the innermost 20" of NGC 3310, a spiral galaxy which like NGC 5953 emits strongly in the radio-frequency region from knots and ridges coincident with giant H II regions close to the nucleus. The H β luminosities given by these authors are 1.8×10^{38} , 5.4×10^{39} , and $3.3 \times 10^{38} \text{ ergs s}^{-1}$ for M33, M101, and M51, respectively, and they range from 3.1×10^{39} to $2.3 \times 10^{40} h^{-2} \text{ ergs s}^{-1}$ in NGC 3310. This last value refers to the supergiant "jumbo" H II region in NGC 3310 (Balick and Heckman 1981), a starburst region, whose angular size $6'' \times 12''$ corresponds to $300 \times 600 h^{-2} \text{ pc}$ (Telesco and Gatley 1984). In a recent investigation Pogge and Eskridge (1987) have found that the total H β luminosi-

TABLE II. Observed and intrinsic FWHMs of NGC 5953 *A*, *B*, *C*.

Component	(FWHM) _{obs} (km s ⁻¹)	(FWHM) _{int} (km s ⁻¹)
A = Nucleus	565 ± 15	380 ± 20
B = West Extension	360 ± 15	
C = East Extension	385 ± 20

FIG. 4. [O III] λ 5007/H β vs [N II] λ 6583/H α , [O III] λ 5007/H β vs [S II] (λ 6716 + H λ 6731)/H α , and [O III] λ 6300/H α vs [O III] λ 6300/H α intensity ratios. The solid curve divides AGNs from H II regionlike objects. Dots labeled A, B, and C represent the Seyfert 2 nucleus, the west component, and the east component, respectively.

ties of extranuclear star-forming regions in a sample of S0 and S0/a galaxies, the morphological type of NGC 5953, range from 5.8×10^{37} to $1.6 \times 10^{40} h^{-2} \text{ ergs s}^{-1}$. Thus, it appears that *B* and *C* have luminosities similar to the brightest giant H II regions in normal spirals and S0 galaxies, and that they are only one order of magnitude fainter than the “jumbo” H II region in NGC 3310. However, the H β luminosity of the regions *B* and *C* should be considered as a lower limit since the Lick spectra have been taken with a slit width which limits the field of view to $2''$ in the north-south direction. No information is lost along the slit (east-west direction) as it is longer than *B* and *C* in that direction. The projected surface areas of *B* and *C* are thus $2'' \times 7.5''$, which correspond at their distance to $200 \times 750 h^{-2} \text{ pc}^2$.

The volume and mass of the emitting regions can be derived from the H β luminosity assuming spherical symmetry, filling factor ϵ , temperatures $T_{A,B,C} = 10^4 \text{ K}$, and photoionization followed by recombination as the main excitation mechanism. The relations

$$L(\text{H}\beta) = L_{100}/h^2 = 4\pi j_\nu V \epsilon,$$

$$M = N_e \epsilon V m_H,$$

where m_H = proton mass, V = volume of the emitting gas, and j_ν = emissivity of H β ($\text{ergs cm}^{-3} \text{ s}^{-1}$) yield the following values of mass and radius of *A*:

$$M_A = 1.4 \times 10^4 h^{-2} M_\odot,$$

$$R_A = 5.0 h^{-2/3} \epsilon^{-1/3} \text{ pc}.$$

Moreover, since the spherical symmetry assumption is not valid for *B* and *C*, their thickness t can be derived by dividing their volume by their projected surface area according to the following relations:

$$S = S_{100}/h^2,$$

$$t = L_{100}/(4\pi j_\nu \epsilon S_{100}).$$

It follows that $S_B = S_C = 1.5 \times 10^5 h^{-2} \text{ pc}^2$, $t_B = 2.3 \times 10^{16} \epsilon^{-1} \text{ cm} \sim 0.007 \epsilon^{-1} \text{ pc}$, $t_C = 9.4 \times 10^{15} \epsilon^{-1} \text{ cm} \sim 0.003 \epsilon^{-1} \text{ pc}$, and the corresponding masses are

$$M_B = 5.0 \times 10^3 h^{-2} M_\odot,$$

$$M_C = 2.1 \times 10^3 h^{-2} M_\odot.$$

c) Optical and Radio Continuum of *A*, *B*, and *C*

The magnitude *B* and the color index ($B - V$) of *B* and *C*, derived convolving their continua with the *B* and *V* response curves of the Johnson photometric system are

$$(V)_B = 16.0, \quad (B - V)_B = +0.3,$$

$$(V)_C = 16.1, \quad (B - V)_C = +0.6.$$

These colors correspond to a spectral type A7-F1 for *B* and F8-G2 for *C* (Pickles 1985), indicating that the stellar population is more evolved for *C* than in *B*. This trend is confirmed by the equivalent width W of the Na D doublet, which corresponds to a spectral type G0-4 ($W = 1.7 \text{ \AA}$) for *B* and to a spectral type K1-2 ($W = 3.8 \text{ \AA}$) for *C*. The mean apparent surface brightness of *B* and *C* are $19.0 \text{ mag arcsec}^{-2}$ and $18.8 \text{ mag arcsec}^{-2}$, respectively. The nucleus *A* has $(V)_A = 14.8$ and $(B - V)_A = 0.7$. Its continuum, dominated by a stellar component (Fig. 3), has a color quite similar to that of the *C* component and corresponds to a spectral type G5-8. In this case the equivalent width of the Na D absorption doublet, $W = 4.9 \text{ \AA}$, corresponds to a spec-

tral type K2-3. The same procedure for deriving the magnitudes, applied to the foreground star, gives as a result: $V_* = 16.0$, $(B - V)_* = 0.6$. The equivalent width of Na D, $W = 2.6 \text{ \AA}$ confirms the spectral type indicated by the color.

The component *B* is in the same position as an extended radio source, which is well separated from the nucleus in the 1.4 and 5.0 GHz radio maps published by Jenkins (1984). The radio source is west of the nucleus, $5''$ distant from it. Its center and east-west diameter correspond approximately to those of the extended emitting region *B*. A rough estimate of the radio fluxes from *B* was made from the maps of Jenkins (1984). The procedure was checked by reproducing the total fluxes of the Seyfert nucleus *A* and its spectral index as published by Jenkins (1984). The fluxes measured in this way are $F_B(5.0 \text{ GHz}) \sim 6 \text{ mJy}$, $F_B(1.4 \text{ GHz}) \sim 14 \text{ mJy}$, which correspond to a nonthermal power-law distribution $F_\nu \propto \nu^{-\alpha}$ with spectral index $\alpha \sim 0.6$. This index is quite peculiar for a H II region, which normally should have $\alpha \sim +0.1$, corresponding to a radio continuum of thermal origin. The observed spectral index, however, is consistent with the emission by relativistic electrons in a magnetic field (synchrotron radiation). These can be produced by local supernovae or by the injection into *B* of material flowing out from the nucleus, for example, within a jet. However, the morphological features shown by the radio map are not typical of a jet, which should be at least four times as long as it is wide (Bridle and Perley 1984).

Models which consider this radio emission to be caused by remnants of supernovae of Type I require a supernova rate in *B* of $\nu_{\text{SN}} = 0.15 h^{-2} \text{ yr}^{-1}$ that remains constant throughout the radio-emitting lifetime of a typical remnant of supernova of Type I, $\tau \sim 20,000 \text{ yr}$ (Ulvestad 1982). The explosion of a supernova of Type I should be easily detectable in *B*, since at maximum it would be brighter than the nucleus *A* itself. Supernovae of Type I have at maximum a typical absolute magnitude $M_B \sim -21$, which would correspond in NGC 5953 to an apparent magnitude $m = 10.6$ for $h = 1$ or $m = 12.1$ for $h = 0.5$. However, we remark that no supernovae have been reported up to now in NGC 5953. In addition, it must be noticed that the integrated color of *B*, $B - V = 0.3$, agrees fairly well with the assumption that supernovae of Type I have exploded in *B*, but cannot account for the frequency of supernovae derived from the radio data. In fact, let us assume that the progenitors of Type I supernovae are the principal components of double systems having mass of the principal component within the range of $1.8 - 3.0 M_\odot$, period in the range of 5–9 yr, and a mass ratio of 0.1–0.4, as suggested by Whelan and Iben (1973). The integrated color of *B* corresponds to age $7 \times 10^8 \text{ yr}$, and to the mass and normalized absolute magnitude of the most evolved stars $M = 2.65 M_\odot$ and $M_V = 2.57$, respectively (Chiosi, Bertelli, and Bressan 1988; Bertelli, Bressan, and Chiosi 1989). It follows that the number of binary systems with mass $2.65 M_\odot < M < 3.0 M_\odot$ which can have produced a supernova of Type I in *B* in the last $7 \times 10^8 \text{ yr}$ is 1.9×10^4 for $h = 0.5$ (4.7×10^3 for $h = 1.0$). These values, derived using the initial mass function of Salpeter (1955) and the percentage of binary stars given by Whelan and Iben (1973), correspond to an average frequency of Type I supernova, $\nu_{\text{SN}} = 2.7 \times 10^{-5} \text{ yr}^{-1}$ for $h = 0.5$, $\nu_{\text{SN}} = 6.7 \times 10^{-6} \text{ yr}^{-1}$ for $h = 1.0$. This discrepancy between the supernova rates derived from radio and optical data rules out the hypothesis of frequent supernova blasts in *B*. This conclusion is further supported by the emission line spectrum of *B*, which does not show any sign of the shock effects

that would be expected if repeated supernovae had sent blast waves into a moderately uniform interstellar medium, creating a large bubble with a very bright shocked rim (Ford *et al.* 1985).

No radio emission appears on the 5.0 GHz map in the position of component *C*. This indicates that any radio emission from *C* is below the lowest contour level, 3 mJy, given on the map. On the other hand at 1.4 GHz, emission up to a level of ~ 1 mJy is present at the position of *C*, but no peculiar radio structures, indicating a source separated from the nucleus, are present there.

IV. ANALYSIS

The spectroscopic and photometric analysis of the extended emitting region *B* and of its gaseous environment shows that its properties are typical of a H II region of extremely high luminosity peculiar for the weakness of the [O III] lines in its spectrum. This could result either from a low degree of ionization or from a high heavy-element content of the emitting gas.

According to the first interpretation, the weakness of [O III] $\lambda\lambda$ 4959, 5007 could be ascribed to the presence in *B* of a stellar population dominated by evolved stars which do not have strong enough ultraviolet radiation to ionize O^+ to O^{++} . However, O^0 , which has the same ionization potential of H^0 , should certainly be ionized to O^+ , and since the electron density in *B* is lower than the [O II] λ 3726, 3729 critical density, $N_e \sim 10^3 \text{ cm}^{-3}$, [O II] $\lambda\lambda$ 3727, 3729 would be strong in the spectrum of *B*. Actually, however, both line ratios [O II] λ 3727/H β and [O III] λ 5007/H β are larger in *C* than in *B*, in disagreement with the presence in *C* of an ionizing stellar population of later spectral type than in *B*. Forbidden [O II] and [O III] lines as faint as in *B* have been observed by Evans (1987) in the heavy-element rich H II region (—029–038) in NGC 1068. This must mean that the heavy-element content, in addition to the degree of ionization, plays an important role in determining the spectrum of the emitting gas in *B*. In fact heavy ions, including O, act as coolants of the emitting gas, and a small increase of their abundance, relative to H, can greatly increase the cooling rate of the gas and thus decrease its temperature. Hence a heavy-element rich emitting region is cooler than a heavy-element poor one, and therefore emits less optical [O III] $\lambda\lambda$ 4959, 5007 and [O II] $\lambda\lambda$ 3726, 3729 radiation, because of the steep temperature dependence of the strengths of these collisionally excited lines. This interpretation was checked by estimating the total O, N, and S abundances in the extranuclear emitting regions in NGC 5953 from their reddening-corrected emission-line ratios. The theoretical calibration of the extragalactic H II region abundance sequence by Dopita and Evans (1986) and the techniques suggested in that paper were used. The results of the abundance determinations by this method are shown in Table III. They indicate that the O content in *B* is a factor ~ 1.5 larger than the solar value and is comparable with the O abundance measured in the high heavy-element rich H II region S5 in M101 (Evans 1986). On the other hand, the relative abundances of N and S are smaller than solar. Estimates of the ionization parameter [$U = Q(H)/4\pi r^2 N_e c$] and of the electron temperature T in the O^{++} zone, derived using the relation

$$12 + \log(O/H) = 13.15 - 0.5903 \log(U_e),$$

are valid for $6.7 \leq \log(U_e) \leq 8.4$. The calibration of T vs $\log(4959, 5007/6548, 6584)$ found for photoionization

TABLE III. Elemental abundances in NGC 5953, *B*, *C*.

Component	$12 + \log(O/H)$	$\log(N/O)$	$\log(S/O)$
B	8.98	−1.30	−1.68
C	8.57	−0.89	−1.27
Adopted Solar	8.82	−1.14	−1.52

models of H II regions by Dopita and Evans (1986) gives as a result:

$$T_B \sim 5700 \text{ K}, \quad U_B \sim 3.9 \times 10^{-4}.$$

It is interesting to note that at this temperature the main cooling is due to the fine structure transitions of [O III] $\lambda\lambda$ 52 μm , 88 μm (Osterbrock 1989) and hence the optical transitions must be very weak, in agreement with the observed spectrum of *B*. In addition, the ionization parameter is comparable with the lowest value of the ionization parameter $U = 1.7 \times 10^{-4}$ found for low excitation (heavy-element rich) H II regions by Dopita and Evans (1986), confirming that both a low degree of ionization and a high heavy-element content very probably characterize *B*. High ionization is not expected in *B* from the photons emitted by the Seyfert 2 nucleus. In fact, the upper limit of the nuclear ionization parameter at the distance of *B*, derived using the nuclear H β luminosity and taking the electron density of *B*, is $U \sim 1.3 \times 10^{-5} h^2$, a factor $\sim 13 h^{-2}$ smaller than the ionization parameter estimated above for *B*. It must be noted that the H β luminosity, used to derive the nuclear ionization parameter at the distance of *B*, was evaluated without correcting the observed H β flux for internal extinction, since we supposed that all the light from the nucleus was reddened by its dust. The greatest observable effect on *B* of the ionizing photons from the nucleus should be an increase in the strength of the emission lines from the low-ionization species in the H^+ , H^0 transition zone at the edge of *B*. This would enhance the strength of [O I] λ 6300 in *B*, since the combined effect of the photoionizations produced by the nucleus and by the internal sources is to increase the thickness of the H^+ , H^0 zone.

The extended emitting region *C*, discovered during this investigation, is a typical giant H II region of low ionization degree. An analysis of its spectrum was carried out using the same procedures adopted for the spectrum of *B*. The results, listed in Table III, show that the O abundance is a factor ~ 0.6 larger than the solar value. Conversely the relative abundance of S and N to O is ~ 1.8 times larger than the solar value. The deduced ionization parameter and electron temperature in the O^{++} zone are

$$T_C \sim 6400 \text{ K}, \quad U_C \sim 1.9 \times 10^{-3}.$$

At this temperature cooling by [O III] $\lambda\lambda$ 4959, 5007 is beginning to be significant, and hence these lines are expected to be visible in the spectrum, as is the case in *C*.

One other, very speculative hypothesis to be considered in order to explain the peculiarities observed in the spectra of *B* and *C*, namely, the faintness of the [O III] $\lambda\lambda$ 4959, 5007 lines, is that they might be the result of loss of ionization

equilibrium. If we imagine that *B* and *C* were once fully ionized by the central nucleus and that the nuclear luminosity decreased abruptly, we expect, as pointed out by Binette and Robinson (1987), a rapid decline of the [O III] $\lambda\lambda$ 4959, 5007 lines, due to efficient recombination charge transfer, and a slower decay of low ionization species such as [O I], [O II], [S II], and [N II], as well as a slow decay of the He II λ 4686 recombination line (Binette and Robinson 1987). Thus, if this model is true we should see in the spectra of *B* and *C* strong lines of [O I], [O II], [S II], and [N II], strong He II λ 4686, but [O III] $\lambda\lambda$ 4959, 5007 would be weak or undetected. The lack of any trace of He II λ 4686 in the spectra of the nucleus, and of *B* and *C* makes this picture inconsistent with our observations and further supports the explanation of the observed line ratios in terms of the high heavy-element content measured in *B* and *C*.

V. CONCLUSIONS

The first and most important result of this investigation is the discovery of the gaseous component *B*, which is the optical counterpart of the radio source 5" west of the nucleus of the Seyfert 2 galaxy NGC 5953. In addition, an extended emitting region *C* has been identified to the east of the nucleus in a position symmetrically opposite to *B*.

The analysis of our optical data and of the radio data published by Jenkins (1984) shows that *B* is peculiar in the high abundance of heavy elements and in its nonthermal energy distribution in the 1.4–5.0 GHz range. Both these facts suggest that the origin of its radio continuum could be ascribed to an accumulation of supernova remnants inside it. However, the optical spectrum is not consistent with the rate of supernovae derived from the radio data. The lack of any sign of an optical or radio jet along the direction of *B* excludes the presence of material injected by the nucleus and further supports the hypothesis of an origin of the observed nonthermal radiation within *B*. However, a careful, deep VLA mapping of the whole nuclear region of NGC 5953 would be necessary to definitely exclude the presence of a connection between the nucleus and the radio knot. Such an investigation would be useful also for a more detailed study of the radio morphology of the extended emitting region *C*.

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