THE ASTROPHYSICAL JOURNAL, 231:307–311, 1979 July 15

SPECTROPHOTOMETRY OF THREE HIGH-REDSHIFT RADIO GALAXIES: 3C 6.1, 3C 265, AND 3C 352

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Received 1978 November 1; accepted 1979 January 26

ABSTRACT

Redshifts and spectrophotometry have been obtained for the high-redshift radio galaxies identified with 3C 6.1, 3C 265, and 3C 352 which have redshifts of $z = 0.840$, 0.811, and 0.806, respectively. 3C 265 has a very rich, strong emission-line spectrum, a nonthermal optical continuum, and a disturbed appearance on deep, direct photographs. 3C 6.1 and 3C 352, while also having emission-line spectra, appear to show stellar galaxy continua as well. The rest-frame $U - B$ colors of 3C 6.1 and 3C 352 are bluer than the integrated colors of nearby elliptical galaxies, suggesting color evolution over the 8×10^9 year look-back time to $z = 0.8$.

Subject headings: galaxies: redshifts — galaxies: spectrophotometry — radio sources: general

I. INTRODUCTION AND OBSERVATIONS

We have been involved in a continuing program of identification and spectroscopy of faint radio galaxies in an attempt to use these luminous galaxies as probes of cosmology and galactic evolution. The status of this program has been reviewed by Smith (1977) and Spinrad and Smith (1977). In this paper we present observations of three radio galaxies with redshifts higher than previously reported (but see Kron, Spinrad, and King 1977, who report a probable cluster redshift $z = 0.95$).

a) 3C 6.1

The identification of 3C 6.1 with a faint ($V \approx 21$) galaxy, published by Longair and Gunn (1975), confirmed an unpublished identification by the authors of this paper from a KPNO 2.1 m image-tube plate. The source, mapped at 5 GHz by Pooley and Henbest (1974) and at 2.7 and 8.1 GHz by Wright (1979), is a nearly symmetric double with the galaxy within 1″ of the radio centroid. We have obtained observations of 3C 6.1 on four nights using the image-dissector scanner (IDS) systems on the Lick Observatory 3 m Shane telescope and the KPNO 4 m Mayall telescope. The summed spectrum is shown in Figure 1*a*. The most striking feature in the spectrum is a strong emission line at λ6859. This feature appears clearly on all three observations covering this wavelength interval. Other features in emission appear at λ7120 and λ7990. The rather low weight of the latter line is due to poor signal-to-noise ratio in that spectral region caused by the strong telluric OH emission. These features may be identified with [O II] λ3727, [Ne III] λ3869, and Hγ, respectively, at a mean redshift $z = 0.8404 \pm 0.0004$. The details of the emission-line spectrum are listed in Table 1. Although the continuum is poorly defined, there does appear to be a change in the continuum level between the [O II] emission and λ4000 rest. We believe that the most likely interpretation of this change in continuum level is the 4000 Å discontinuity seen in the spectra of normal galaxies. If this interpretation is correct, we have detected a stellar population at $z = 0.84$, younger by 8×10^9 years than the late-type population which dominates the light of nearby galaxies.

b) 3C 265

The radio source 3C 265 has been identified with an asymmetric galaxy by two of us (G. G. and M. V.), and the same identification has recently been published by Kristian, Sandage, and Katem (1978) and by Laing *et al.* (1978). A deep, direct red photograph of the field of 3C 265 (Kodak IIIa-F + GG 495) obtained with the KPNO 4 m telescope is shown in Figure 2 (Plate 4). The radio source is an asymmetrical double (Mackay 1969), and Figure 2 shows a chain of five objects that fall along the axis of the double source. The galaxy marked in Figure 2 is identified with the radio source based on its proximity to the radio centroid. The chaotic form of the galaxy identified with the radio source suggests activity or

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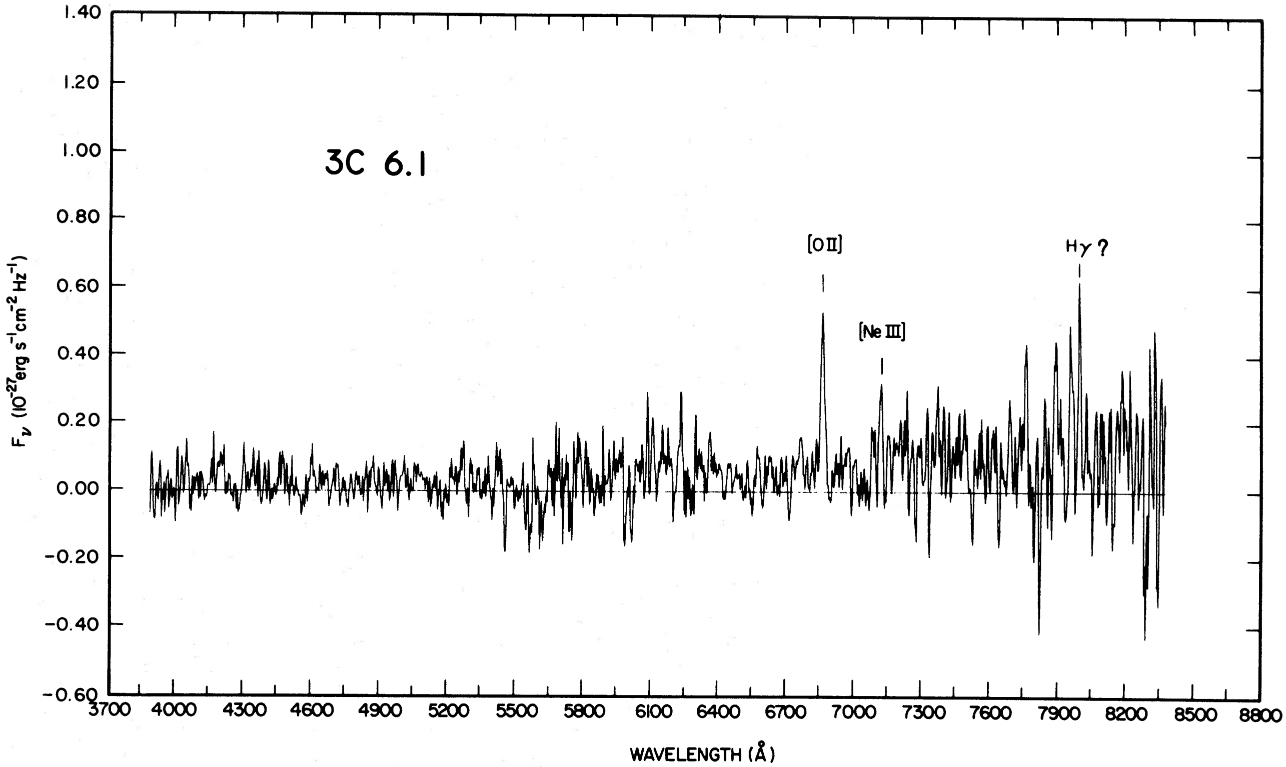

FIG. 1*a*

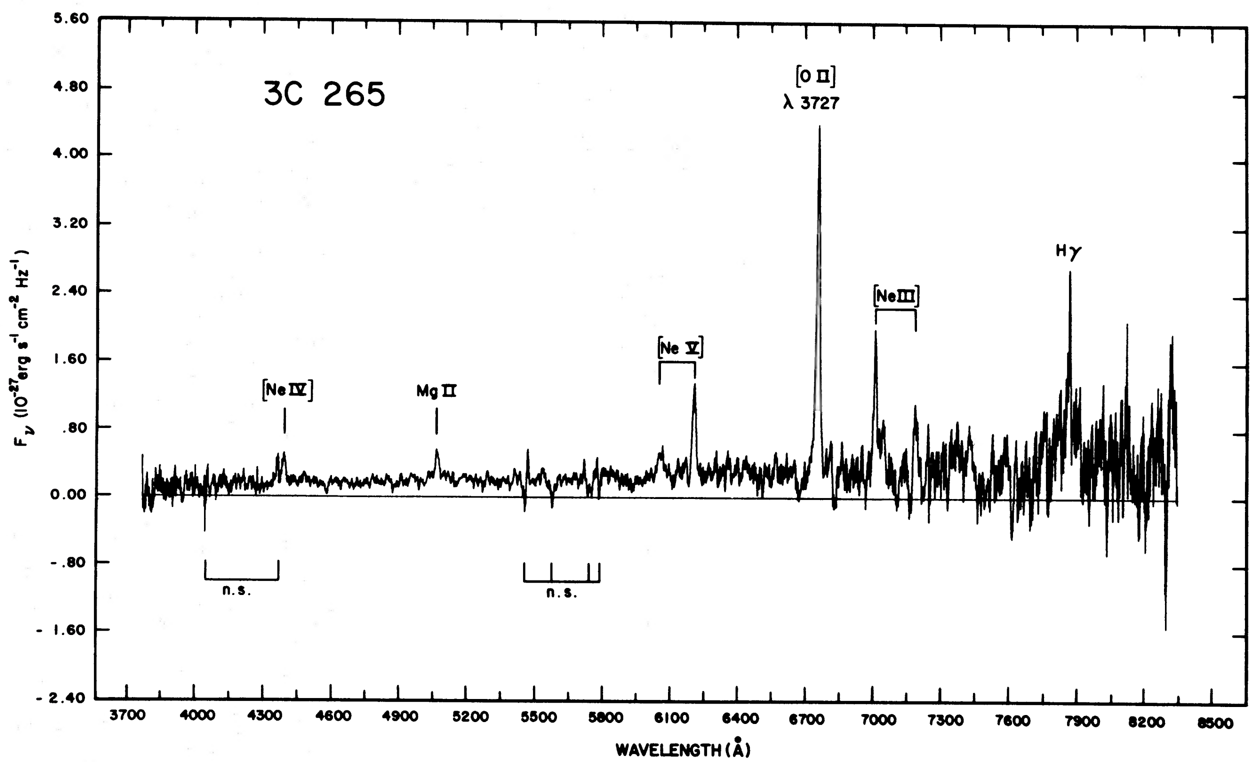

FIG. 1*b*

FIG. 1(*a*), (*b*), (*c*).—IDS observations of the spectra of high-redshift radio galaxies 3C 6.1, 3C 265, and 3C 352

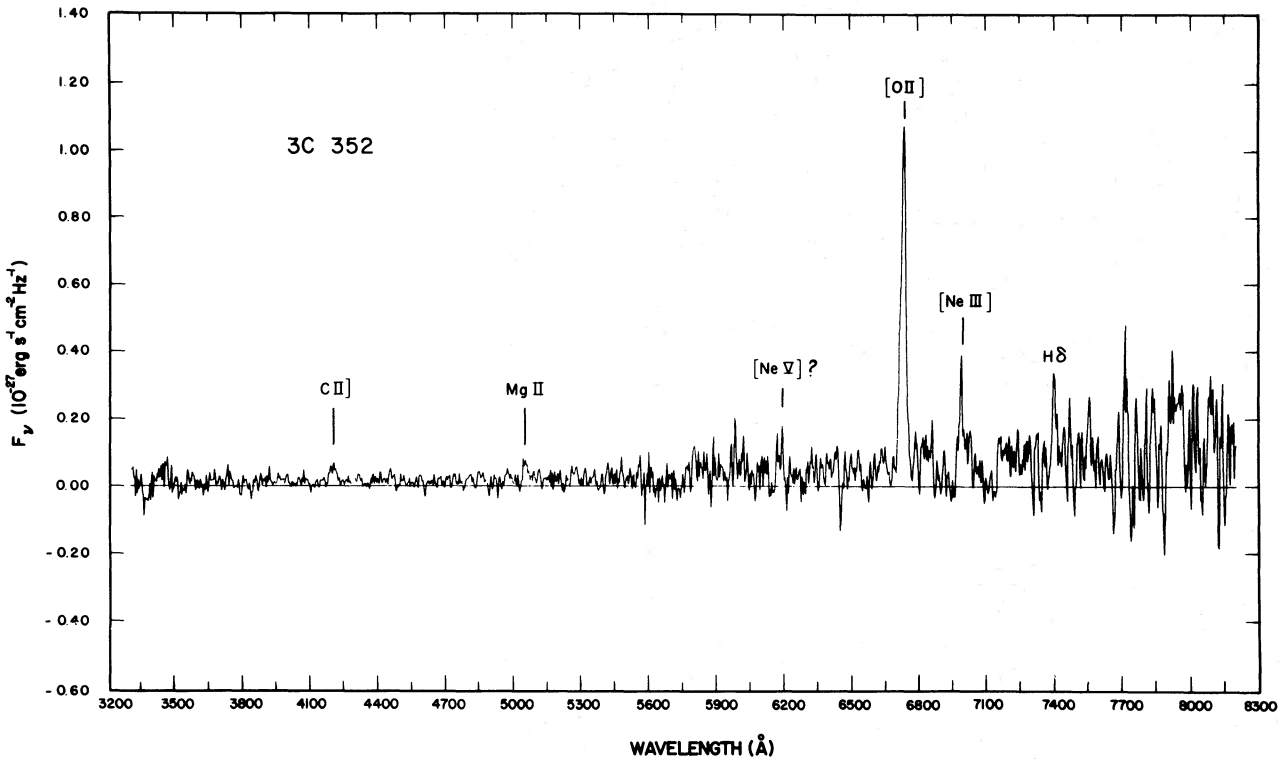

FIG. 1c

FIG. 1.—*Continued*

TABLE 1

REST-FRAME EMISSION-LINE SPECTRA OF 3C 6.1, 3C 265, AND 3C 352

ID	λ_0 (Å)	λ_{obs} (Å)	z	W_λ (Å)	I_λ (10^{-15} ergs cm^{-2} s^{-1})
3C 6.1:					
[O II]...........	3727	6859	0.8404	70	1.7
[Ne III]..........	3869	7120	0.8404	20	0.6
Hγ.............	4340	7990	0.8410	30	0.9
3C 265:					
[Ne IV]..........	2424	4388	0.8102	22	3.2
Mg II...........	2799	5064	0.8092	22	2.8
[Ne V]..........	3346	6059:	0.8108:	16:	2.0:
[Ne V]..........	3426	6203	0.8106	37	4.8
[O II]...........	3727	6750	0.8110	141	17.2
[Ne III]..........	3869	7006	0.8108	44	5.5
[Ne III]..........	3968	7185	0.8107	15	1.9
Hδ.............	4101	7422:	0.809:	...	...
Hγ.............	4340	7860	0.8111	50	5.9
3C 352:					
C II]............	2326	4200	0.8056	55	0.7
Mg II...........	2799	5050	0.8042	40	0.5
[O II]...........	3727	6730	0.8057	300	6.1
[Ne III]..........	3869	6985	0.8054	55	1.1
Hδ.............	4101	7406	0.8059	35	0.8
Hγ?............	4340	7838	0.8059	72	0.3

interaction with nearby galaxies; it is also possible, however, that the apparent asymmetry is due to superposition of nearby images. Observations of 3C 265 have been obtained with the Lick IDS on four nights in 1976 and 1977, covering the wavelength range λλ3700–8340. The spectrum of 3C 265, reproduced in Figure 1*b*, shows very strong, high-excitation emission lines, similar to the spectrum of Cygnus A (Osterbrock and Miller 1975). The Mg II resonance doublet and [Ne IV] λ2424 are also seen in emission. The continuum appears to be nonthermal with a spectral index $\alpha = 1.1 \pm 0.2$ ($F_\nu \propto \nu^{-\alpha}$). Our results are consistent with the broad-band colors $(B - V) = 0.2$–0.4 obtained by Kristian, Sandage, and Katem (1978) and Saslaw, Tyson, and Crane (1978). There is no obvious sign of a stellar continuum in the spectrum of 3C 265. The details of the emission-line spectrum are given in Table 1. We derive an emission-line redshift $z = 0.8108 \pm 0.0002$.

Scans were also obtained of the brighter, red galaxy to the east of 3C 265. It has an absorption-line spectrum without obvious peculiarity. We obtain a redshift $z = 0.392$ from the 4000 Å break and the G-band; thus this galaxy does not appear to be physically related to the radio galaxy. The two objects farther east appear to be stellar, both on our direct plate and from SIT data quoted by Kristian, Sandage, and Katem (1978). To our knowledge, spectroscopic observations of these objects have not yet been made.

c) *3C 352*

Kristian, Sandage, and Katem (1974) have identified 3C 352 with a faint extended object that coincides within 1″ with the precise radio position of Adgie, Crowther, and Gent (1972). Figure 3 (Plate 5) shows a deep red (Kodak IIIa-F + GG 495) plate of the field around 3C 352 taken with the KPNO 4 m telescope. The identification appears to be a centrally concentrated, apparently elongated galaxy SE of a 16th magnitude star. IDS observations of 3C 352 were obtained on six nights at Lick and Kitt Peak Observatories. Figure 1*c* shows the sum of these data. Similar to 3C 6.1, 3C 352 shows a single strong emission line which we identify as [O II] λ3727 at a redshift $z = 0.806 \pm 0.001$. Other, weaker features may then be identified as C II] λ2326, Mg II λ2799, [Ne III] λ3869, and Hδ. A weak feature near λ6180 might be [Ne V] λ3426, but the redshift from that line is discrepant by an amount greater than the error in our wavelength determination. If our identification of Hδ is correct then Hγ should be present at λ7840 with an intensity at least 50% greater than Hδ. There is a feature at the proper position; however, its strength is less than Hδ. This is a very noisy region of the spectrum, however, owing to the very strong telluric OH emission.

3C 352 shows a weak but almost certainly real feature at the proper position to be the Mg II doublet, which is marginally resolved into the individual components. It is curious that Mg II λ2799 is almost never identified in the emission line spectra of narrow-lined radio galaxies such as 3C 295 and those discussed here and in Spinrad, Kron, and Hunstead (1979), while the Mg II doublet is one of the stronger features in QSO spectra. The weakness of Mg II may suggest that the ionized region in narrow-lined radio galaxies is density-bounded, since Mg II is generally thought to be produced in the transition region between the H II and H I regions. It would be interesting to see if, in those galaxies which exhibit broad and narrow components to the Balmer lines, Mg II exhibits a similar profile, or if perhaps the narrow component is absent.

To our knowledge, this is the first report of the C II] λ2326 intercombination line emission in a galaxy spectrum. This may not be surprising since this feature is accessible to ground-based telescopes only for $z \gtrsim 0.4$.

In the spectrum of 3C 352, there appears to be a discontinuity in the continuum, rather more distinct than in 3C 6.1, at about λ7165. If interpreted as the "4000 Å break," this feature yields a redshift $z = 0.79$ in fairly good agreement with the emission-line redshift. Thus, in 3C 352, as well as in 3C 6.1, there is the possibility of having detected a stellar population.

II. DISCUSSION

The large redshifts reported here represent distances and look-back times that are great enough that cosmological effects, owing to both world model and evolution, are relatively large. For $z = 0.8$ the difference between the $q_0 = 1$ and $q_0 = 0$ Friedmann models is over 3/4 magnitude in the redshift-magnitude diagram. Despite the fact that the small aperture (3″) used for these observations makes the absolute calibration somewhat uncertain, we have used our data to place 3C 6.1 and 3C 352 on the Hubble diagram for 3C radio galaxies as described by Smith (1977). We measure observed, emission-corrected V-continuum magnitudes on the scanner system $V_{\rm SC} = 24.4$, 20.7, and 23.2 for 3C 6.1, 3C 265, and 3C 352, respectively. Because of the strong nonthermal continuum of 3C 265, we will disregard it in the following discussion. For both 3C 6.1 and 3C 265, the continuum detection is very poor at observed V (plus the K correction is uncertain for $z \gtrsim 0.72$), and rest V lies longward of our spectral coverage. We have therefore calculated the corrected V-magnitude by taking the scanner magnitude at *rest B* and assuming a color $(B - V)_{\rm REST} = 0.9$ appropriate for the integrated color of a giant elliptical galaxy. Owing to the small aperture used, the error in the magnitude may be as large as several tenths; however, most known sources of error (seeing, guiding errors, etc.) tend to underestimate the brightness of the galaxy. For comparison with previous studies we have adopted the aperture correction of Sandage (1972) which amounts to about 0.6 mag in each case. $B_{\rm REST}$ falls longward of 7900 Å for $z > 0.8$; thus for 3C 352 ($b^{\rm II} = 36°$) reddening is negligible. However, 3C 6.1 is nearer the galactic plane ($b^{\rm II} = 17$) where Heiles (private communication) suggests $E_{B-V} \approx 0.2$ from the $N_{\rm H\,I}$ column density (Heiles and Habing 1974; Burstein and Heiles 1978). This implies an extinction of approximately 0.35 mag at redshifted $B_{\mathrm{REST}} = 8100$ Å (Nandy *et al.* 1975). We thus derive corrected scanner magnitudes $V_{\mathrm{CORR}} = 19.5$ and 20.2 for 3C 6.1 and 3C 352, respectively. Comparison with recent published studies of the Hubble Diagram for 3C radio galaxies (Smith 1977) and first-ranked cluster galaxies and radio galaxies (Kristian, Sandage, and Westphal 1978) shows that these objects lie 0.8 mag and 0.1 mag, respectively, above the straight line for $q_0 = 1$. This is also the case for most other galaxies observed with $z \gtrsim 0.4$, suggesting a value of q_0, uncorrected for galactic evolution, in excess of 1. Grasdalen's (private communication) 2 μm photometry of distant radio galaxies (including 3C 265) also suggests an apparent $q_0 \approx 2$.

During the past few years it has become apparent that the evolution of the stellar population (and possibly also dynamical evolution) in galaxies may dominate other cosmological effects in tests such as the redshift-magnitude test. For example, reasonable models of the evolution of galaxies (see Tinsley and Gunn 1976) suggest that correction for luminosity evolution may revise the value q_0 downward by as much as 1.5 from that derived from uncorrected data. Detecting color evolution, which is likely to be smaller by a factor of 3 or so than the change in luminosity (Tinsley and Gunn 1976), is one promising way of understanding the evolution of the stellar population in these galaxies. From our spectrophotometry, we find rest frame colors on our scanner system, $(U - B)_{\mathrm{SC}} = 0.45, 0.85$ for 3C 6.1 and 3C 352, respectively. These may be compared with the nuclear color for M32 (which is comparable to the integrated color of a gE galaxy) of $(U - B)_{\mathrm{SC}} = 1.2$. While the error in the color may be as large as 0.4 mag, these measures support the suggestion of Spinrad and Smith (1977), that the colors of galaxies evolve by an amount $\Delta(U - B) \gtrsim 0.4$ from $z = 0.8$ to the present. This is somewhat larger than predicted by Tinsley and Gunn (1976) models, with z, the slope of the initial mass function, equal to 1.

All of the above considerations, of course, rest upon the presumption that we are seeing the light from the late-type stellar component of an E galaxy, undiluted by nonthermal radiation, hot stars, etc. The very blue color and high luminosity for 3C 6.1 might suggest the presence of such a component; if approximately 60% of the light at B_{REST} were due to a power-law continuum with $\alpha = 1$, the observed color and luminosity could be reproduced. However, particularly in 3C 352, we believe we are seeing the stellar 4000 Å continuum discontinuity which would be washed out by any significant nonthermal component. In addition, the emission-line spectra of 3C 6.1 and 3C 352 strongly resemble 3C 295 and other low-excitation, narrow-lined radio galaxies which do not generally show the presence of a strong nonthermal component. Nonetheless, conclusions based on such objects must be treated with some caution until a more detailed study can be made.

We wish to thank Margaret Burbidge who has assisted in this program by the contribution of observing time and encouragement. This work has been supported by the National Science Foundation under grants AST 77-22560 to UCSD and AST 77-26897 to Berkeley.

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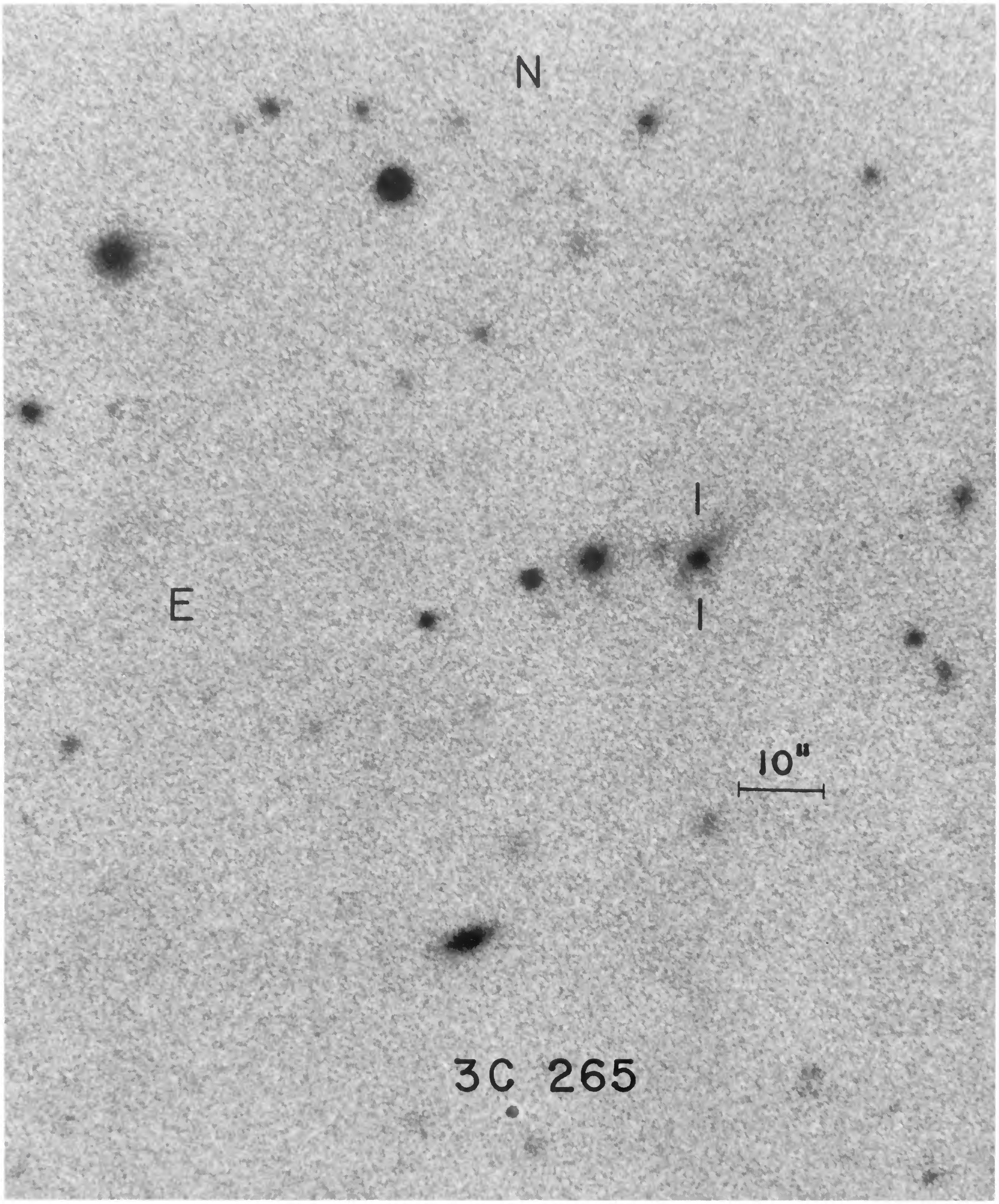

FIG. 2.—KPNO 4 m photograph of 3C 265 (Kodak IIIa-F + GG 495). The radio galaxy is marked ($\alpha_{1950} = 11^h42^m52^s.39$; $\delta_{1950} = 31°50'29''.0$).

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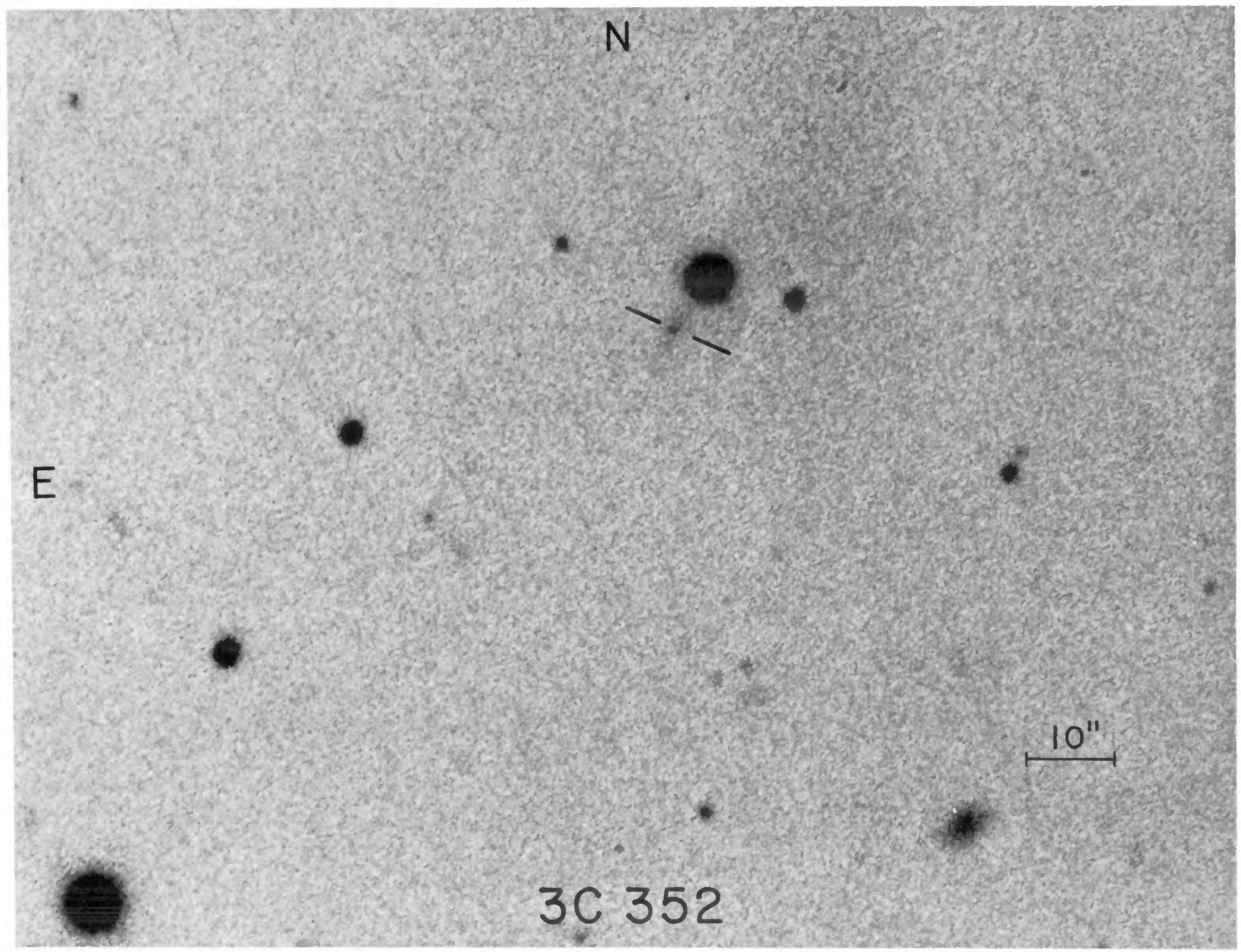

FIG. 3.—KPNO 4 m photograph of 3C 352 with the radio galaxy marked ($\alpha_{1950} = 17^h\ 09^m\ 18^s.0$, $\delta_{1950} = 46°\ 05'\ 06''$). IDS observations of the object NW show it to be a galactic star.

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