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AN EXCEPTIONALLY BRIGHT, COMPACT STARBURST NUCLEUS

BRUCE MARGON[1,2]
Department of Astronomy, University of Washington
SCOTT F. ANDERSON[1] AND MARIO MATEO[1]
Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington
MICHEL FICH
Department of Physics, University of Waterloo
AND
PHILIP MASSEY
Kitt Peak National Observatory, National Optical Astronomy Observatories
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We report observations of a remarkably bright ($V \sim 13$) starburst nucleus, 0833+652, which we have detected at radio, infrared, optical, ultraviolet, and X-ray wavelengths. Despite an observed flux at each of these wavelengths which is comparable to that of NGC 7714, often considered the "prototypical" example of the starburst phenomenon, 0833+652 appears to be a previously uncataloged object. Its ease of detectability throughout the electromagnetic spectrum should make it useful for a variety of problems in the study of compact emission-line galaxies.

Subject headings: galaxies: individual (0833+652) — galaxies: nuclei — radio sources: galaxies — ultraviolet: spectra

I. INTRODUCTION

During the course of a program aimed at discovering quasi-stellar objects lying within high galactic latitude fields also imaged by the *Einstein Observatory* (Anderson and Margon 1987), we obtained in 1983 January, and 1984 January and February, several "grism" plates of a field centered on the bright star π^2 UMa, using the Mayall 4 m reflector of the Kitt Peak National Observatory. These plates included IIIa-F and IV-N emulsions, thus providing low-dispersion spectra throughout the 0.32–0.9 μm range of all objects to moderately faint limiting magnitudes. The details of these observations have been reported elsewhere (Anderson and Margon 1987). During examination of these plates, we noted a remarkably bright, slightly extended object with obviously strong Balmer, [O II], and [O III] emission lines at low ($\leq 10^4$ km s^{-1}) velocity. On the Palomar Sky Survey, the object is sufficiently compact that it can be mistaken for a bright star at first glance, but it is noticeably extended when subjected to close examination. The coordinates, to accuracy $\pm 5''$, are $\alpha(1950) = 08^h33^m57^s.4$, $\delta = 65°17'46''$. Although not obvious to us at this point whether the object was galactic or extragalactic, we were quite surprised to find that despite its prominence, very strong emission spectrum, and northern location, 0833+652 does not appear to be a previously cataloged object.

The object is sufficiently bright that, in a series of observations described below, we have detected it over a frequency range of eight decades. We argue that it is one of the brightest known "starburst" nuclei, and, as one of the very few objects easily detectable over such a broad wavelength interval, will be useful for a variety of future studies. In most of its properties it is remarkably similar to, although somewhat more intrinsically luminous than, NGC 7714, termed that "prototypical" starburst by Weedman *et al.* (1981).

II. OBSERVATIONS

a) Optical Spectroscopy and Imaging

The extragalactic nature of 0833+652 was easily clarified via spectrophotometry of the object obtained in 1985 April, using the intensified Reticon scanner at the No. 2 0.9 m reflector of the Kitt Peak National Observatory. The observations, which have spectral resolution of ~12 Å, were reduced to absolute flux via observation of several spectrophotometric standard stars, and the resulting blue and red spectral scans are shown in Figures 1*a* and 1*b*, respectively. The velocity of the object, averaged from 12 emission lines, is 5700 ± 120 (m.e.) km s^{-1}. Although much of the optical flux is contained in the emission lines, and so the continuum and broad-band magnitudes differ considerably, it is immediately clear that this is an object of galaxian luminosity ($M_{5500\,Å} \sim -21$ for $H_0 = 75$ km s^{-1} Mpc^{-1}, assumed hereafter). The narrow emission lines (unresolved at our ~700 km s^{-1} spectral resolution), strength of Hβ relative to [O III] λ5007, and presence of [O II] λ3727, all suggest that this is a starburst nucleus (e.g., Weedman *et al.* 1981) rather than a nonthermal active galaxy (Baldwin, Phillips, and Terlevich 1981; Balzano 1983). The Mg *b* λ5175 absorption band from starlight in the galaxy is strongly detected at the appropriate velocity; the λ4300 G band is probably also present in absorption, but may be partially filled in by [O III] λ4363 emission. It is thus clear that starlight makes a major or possibly dominant contribution to the continuum of this object. In Table 1 we list the intensities of the most prominent spectral features.

The steepness of the observed Balmer decrement indicates that extinction is significant, and it is almost surely local to the object at this galactic latitude ($b = 36°$). We have assumed an

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by AURA Inc., under contract with the NSF.

[2] Guest Observer, *International Ultraviolet Explorer*.

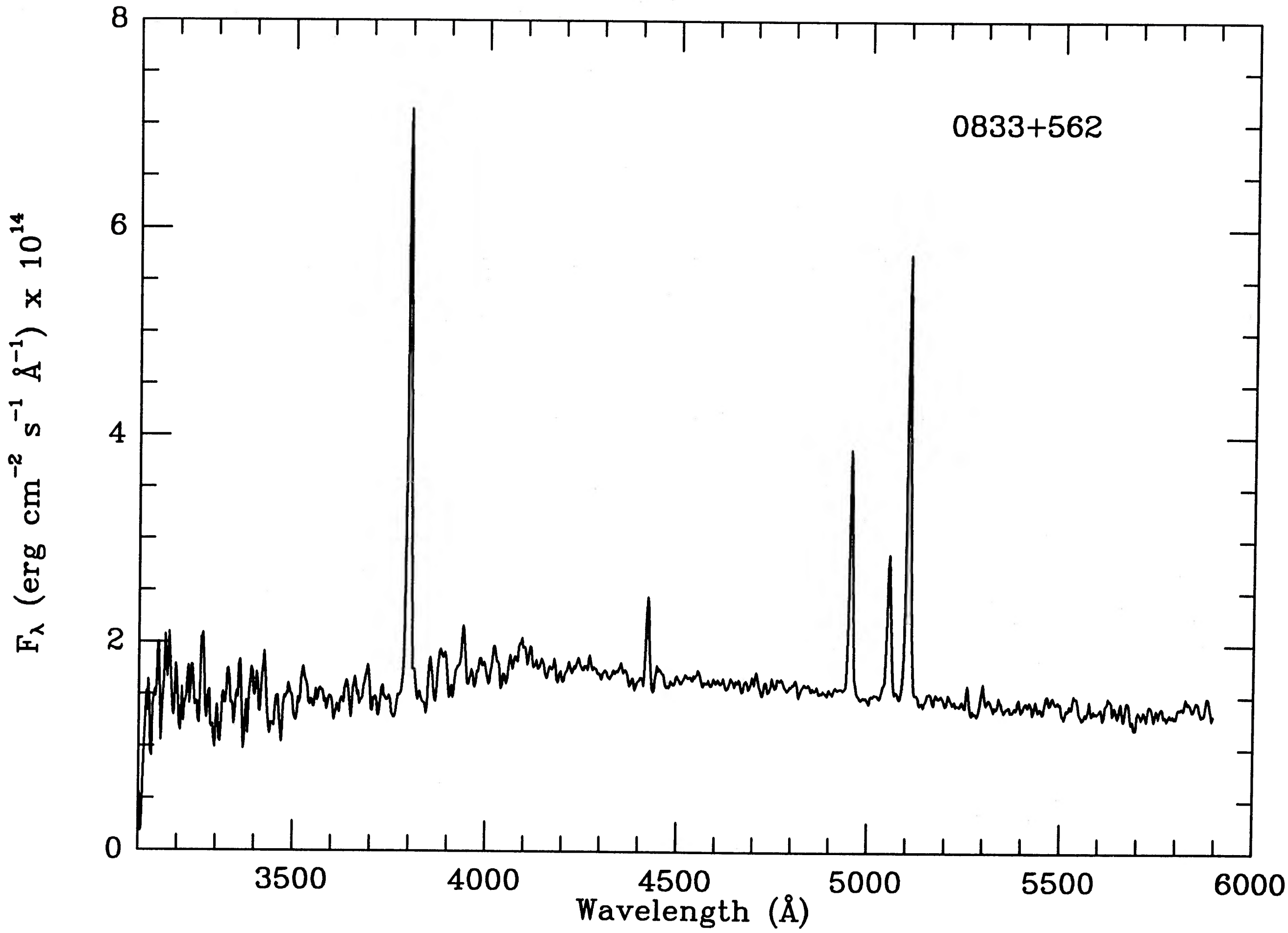

FIG. 1*a*

FIG. 1.—(*a*) The blue spectrum of 0833+652, observed through a 22″ diameter aperture, with the Kitt Peak No. 2 0.9 m reflector and the intensified Reticon scanner. This 5000 s exposure was obtained on 1985 April 22. Note the prominent Mg *b* absorption band near λ5270. (*b*)—The red spectrum, a 1400 s integration made on 1985 April 19, obtained with a similar instrumental configuration as in Fig. 1*a*.

intrinsic Hα/Hβ decrement appropriate for case B recombination at $T = 10^4$ K, $n_e = 10^4$ cm^{-3} (Brocklehurst 1971), and corrected the line intensities using the extinction curve tabulated by Rayo, Peimbert, and Torres-Peimbert (1982); French (1980) has discussed the assumptions attendant in such a procedure. These corrected intensities also appear in Table 1. We infer $E(B-V) = 0.55$; uncertainties in the measured intensities and the appropriate extinction corrections must surely contribute an uncertainty of 0.05 mag to this value. Our inferred color excess is quite similar to the values of 0.49 and 0.53 derived for NGC 7714 by van Breugel *et al.* (1985) and French (1980), respectively, and our corrected line intensities are also similar.

A variety of alternative extinction estimates are potentially available from our data, but all prove to have pitfalls. We do have a measured Lyα intensity, to be discussed below, but as it is obtained with a different technique and different aperture from the visible data, any resulting Lyα/Hβ decrement must be viewed with caution. Decrements of the higher order Balmer lines are in principle quite useable, but these features are rather weakly detected in our relatively brief exposures. The nominal strengths of Hγ and Lyα in our data are in fact consistent with the color excess we suggest above.

The morphology of the object also supports the starburst nucleus classification. Figure 2 (Plate 2) displays a portion of one of our grism plates of 0833+652. Although this bright object is overexposed, it is still quite evident that the emission lines are not confined to the nucleus of the galaxy, but rather come from a considerably extended region. Despite the poor dynamic range of these photographic data, there is evidence for a faint, extended armlike feature to the NE of the nucleus, and this extension can also be seen to be an emission-line source.

We obtained better direct images of 0833+652 on 1986 June 7, using a CCD at the No. 1 0.9 m reflector on Kitt Peak. The *f*/7.5 secondary dictated by the requirements of other observing programs yields a scale of 0″86 pixel^{-1} at the detector. The data were flat-fielded using standard techniques. The sum of two 250 s exposures in the *B* band is shown in Figure 3. The superior dynamic range of these data now reveal that at lower surface brightness levels, the galaxy is in fact quite extended. In Figure 4, we compare the radial dependence of the surface brightness of 0833+652 with that of a nearby star on the same

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PLATE 2

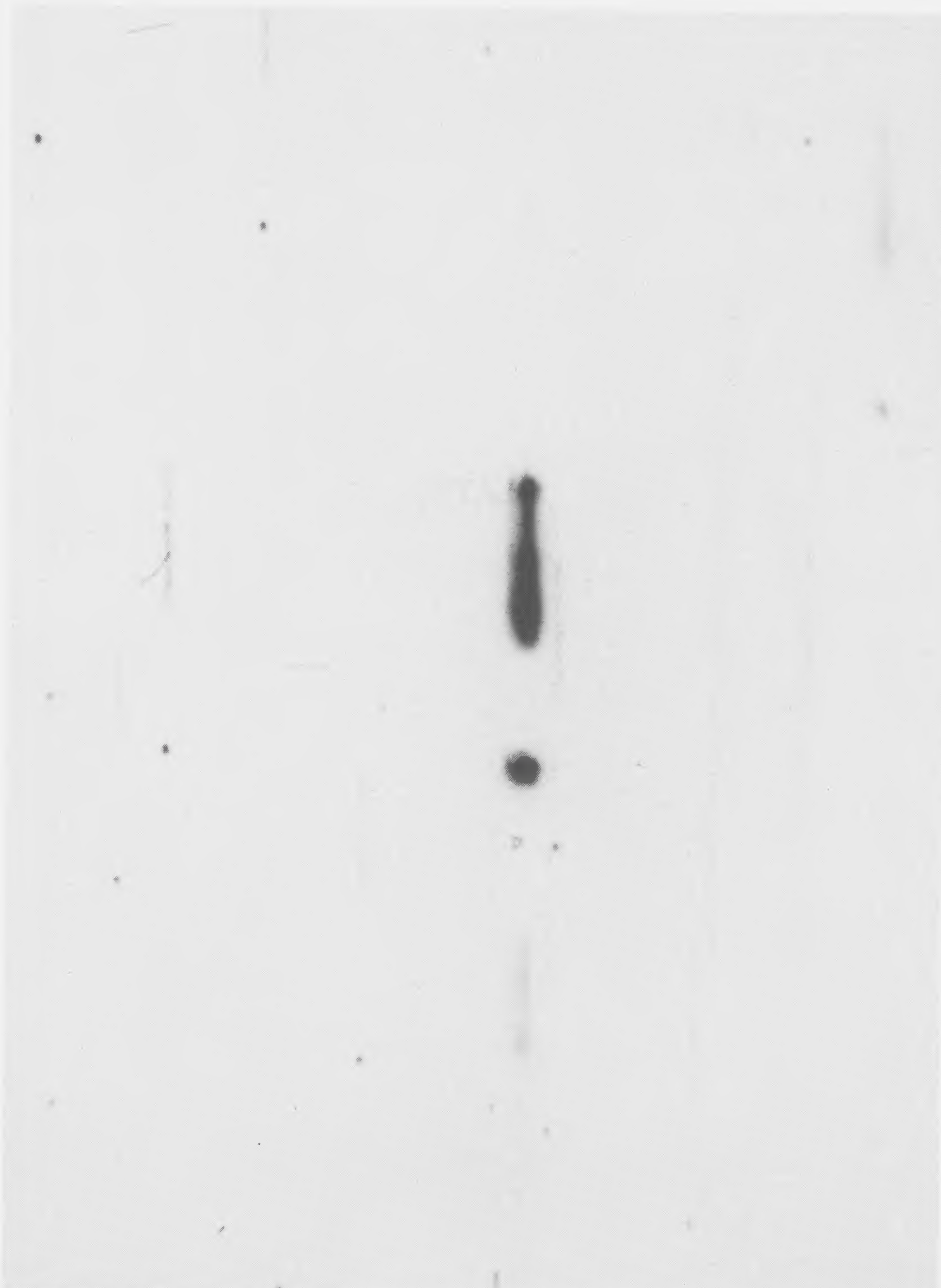

FIG. 2.—An enlargement of a portion of one of the red sensitive grism plates, obtained with the Mayall 4 m reflector. North is up, and east, to the left. The spectrum covers the $\lambda\lambda$3200–6900 range, with the blue end closest to the zero order image. Note that the prominent Hα, Hβ/[O III], and [O II] emission originates not only from the nuclear region, but also from the extended structure to the NE. The plate was optimized for detection of faint quasi-stellar objects, so the galaxy 0833 + 652 is badly overexposed.

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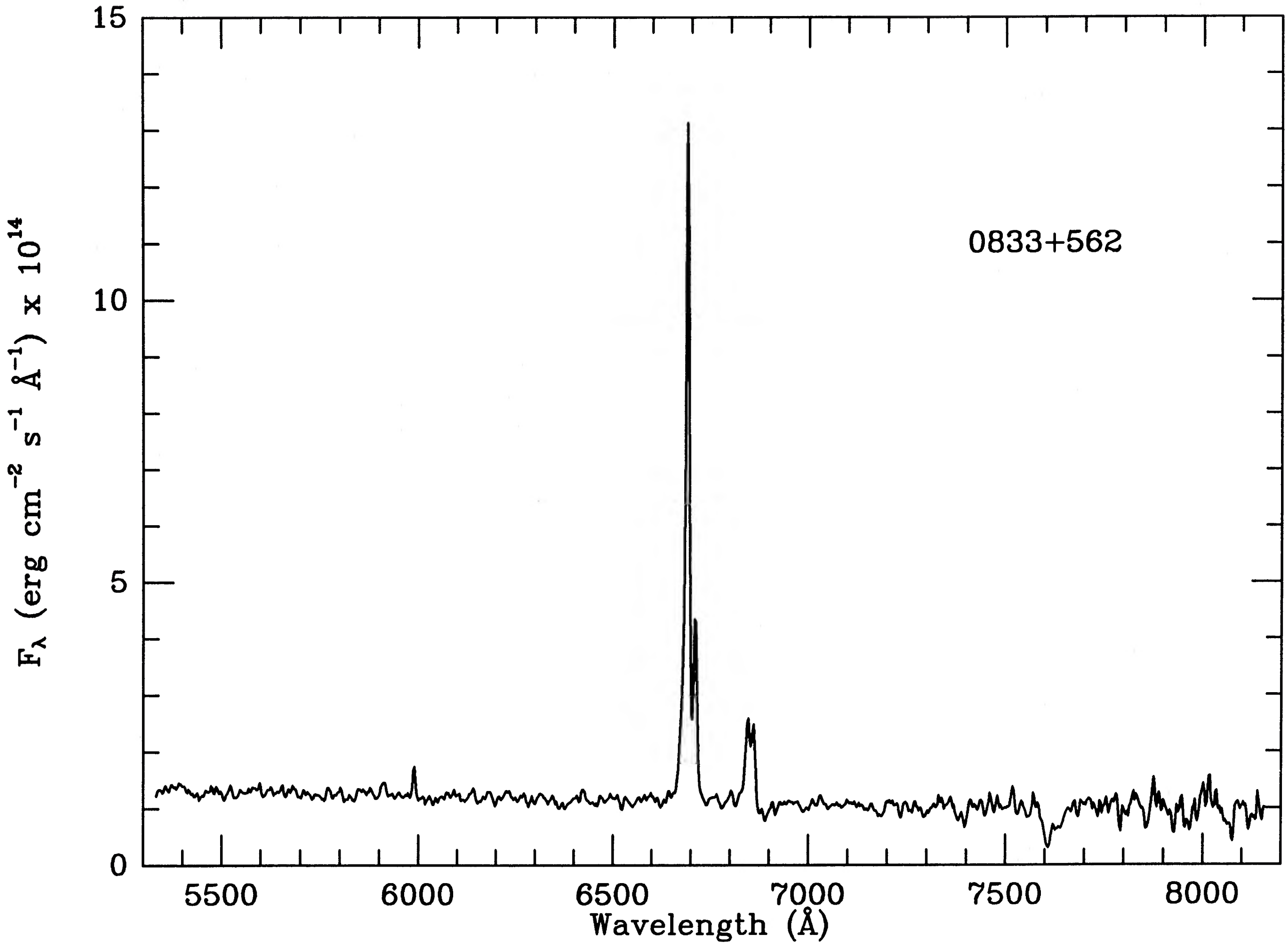

FIG. 1*b*

image; the marked extension of the galaxy is obvious. To a limiting surface brightness of ~0.5 of the night sky, we detect the object at least to a diameter of 30″, corresponding to a linear extent of 11 kpc at the observed redshift. Similar results were also obtained in the *V* band.

b) *Infrared Photometry*

This object appears (anonymously) in the *IRAS Point Source Catalog* (1985), as IRAS 08339+6517. There can be little doubt in our suggested identification, as the positional agreement is excellent, and, as discussed further below, the reported fluxes are in good agreement with an extrapolation of our visible spectrophotometry. The tabulated *IRAS* fluxes are 0.35, 1.13, 5.93, and 6.58 Jy at 12, 25, 60, and 100 μm, respectively. The implied far-infrared luminosity is $\sim 8 \times 10^{10}\ L_\odot$, near the high end of, but well within the range of, luminosities of numerous other starburst galaxies observed with *IRAS* (Deutsch and Willner 1986, 1987).

c) *Radio Observations*

We observed 0833+652 twice at the Very Large Array of the NRAO,[3] at 14.94 GHz in the B-array configuration, and at 4.86 GHz with the C-array. The B-array observations were made on 1985 May 9 using two 50 MHz wide passbands centered on 14.965 and 14.915 GHz, and with a total integration time of 290 s. The nearby phase calibrators OJ 499 and 0859+681 were used, and 3C 286 was employed as a primary flux calibrator, with a total assumed flux density of 3.48 Jy at this frequency. The data from the two passbands were combined after calibration, and images were made with various combinations of taper, weighting, and pixel size. The images were cleaned with the standard NRAO CLEAN algorithm, using various values of the control parameters. No source was detected at the position of the galaxy in any of these images. The "best" synthesized beam possible with these data has diameter ~0″.4. The best image at this resolution shows no source at a 1 σ level of 1 mJy. With a strong taper of resolution 5″, to allow sensitivity to extended structure, the noise level (1 σ) is 20 mJy, and again no source is visible.

The C-array observations were made on 1985 July 30, using two 50 MHz wide passbands centered on 4.885 and 4.835 GHz, and with total integration time of 270 s. The object 0836+710 was used as a phase calibrator; the primary flux calibrator was again 3C 286, assumed to have total flux of 7.41 Jy at this frequency. The data from the two passbands were combined after calibration, and images with uniform weight and no applied taper were constructed. The resulting image, shown in Figure 5, has a pixel size of 1″, resolution of 6″ × 5″, and noise level after CLEANing of 0.5 mJy. Flux is

[3] The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

OPTICAL AND ULTRAVIOLET LINE INTENSITIES OF 0833+652

Identification	λ_{obs}(Å)	Intensity[a]	I_{corr}[b]
Lyα λ1216	1239	100	2300
C IV λ1549	1577:	−78	...
[O II] λ3727	3797	250	420
[Ne III] λ3869	3941	22:	30:
Hδ	...	<9	<10
Hγ	4422	35	40
[O III] λ4363	...	<9	<10
Hβ	4954	100	100
[O III] λ4959	5053	61	57
[O III] λ5007	5102	180	170
He I λ5876	5989	22:	15:
[O I] λ6300	...	<13	<7
Hα	6688	520[c]	280
[N II] λ6584	6709	130	66
[S II] λ6717[d]	6845	65	33
[S II] λ6731[d]	6859	61	31

[a] Intensities are continuum-subtracted peak intensities (no lines are resolved) normalized to Hβ = 100, measured in a 22″ diameter (optical data) or 10″ × 20″ (UV data) aperture. Negative values denote absorption. Estimated uncertainty of wavelength measures is 1 Å. Estimated intensity uncertainty is less than 10% except where suffixed by ":". The integrated observed Hβ flux is 2.5×10^{-13} ergs cm^{-2} s^{-1}.

[b] The intensity corrected for extinction equivalent to $E(B-V) = 0.55$, normalized to Hβ = 100.

[c] Presumably there is a contribution from [N II] λ6548, but the strength of [N II] λ6584 suggests that any correction is small.

[d] The [S II] doublet is partially blended at our spectral resolution, and has been fitted with two Gaussians, each with FWHM 5 Å, plus a linear fit to the continuum, to yield the tabulated results.

clearly detected, consisting of a 7.2 mJy point source centered at $\alpha(1950) = 08^h33^m56^s.9$, $\delta = 65°17'45''$ (a position in good agreement with that of the optical image), and two arclike features extending to the north and east. The extended features are detected at significance of 2–3 σ only and are thus of marginal believability. The entire object has a total flux density of 9.2 mJy at 4.86 GHz. The total implied 6 cm luminosity is close to that of well-studied starburst nuclei such as NGC 7714 (Weedman *et al.* 1981) and NGC 2782 (Kinney *et al.* 1984) at similar frequencies.

d) Ultraviolet Observations

We obtained a low-dispersion ultraviolet spectrum of 0833+652 in 1985 June, using the short-wavelength camera of the *International Ultraviolet Explorer*. The result of a 4700 s exposure in the large (10″ × 20″) *IUE* aperture is shown in Figure 6. Evident features include the apparent detection of Lyα emission, which at this redshift is well-resolved from the geocoronal line, as well as strong C IV λ1549 absorption, superposed on a well-detected, flat continuum. Additional absorption due to Si IV λ1400 may be present, but is certainly not well-detected. A feature near He II λ1640 is almost surely not genuine, as He II λ4686 is not seen in the visible spectrum (Fig. 1*a*) which is of better quality. Some further details of the data appear in Table 1.

The ultraviolet spectrum of 0833+652 is remarkably similar to that of NGC 7714 given by Weedman *et al.* (1981), both in features present, and also in absolute flux. Of particular note is the fact that C IV is strongly in absorption rather than emission, interpreted by Weedman *et al.* as rather conclusive evidence that objects such as these are not related to Seyfert II nuclei. The long-wavelength end of our *IUE* spectrum is an

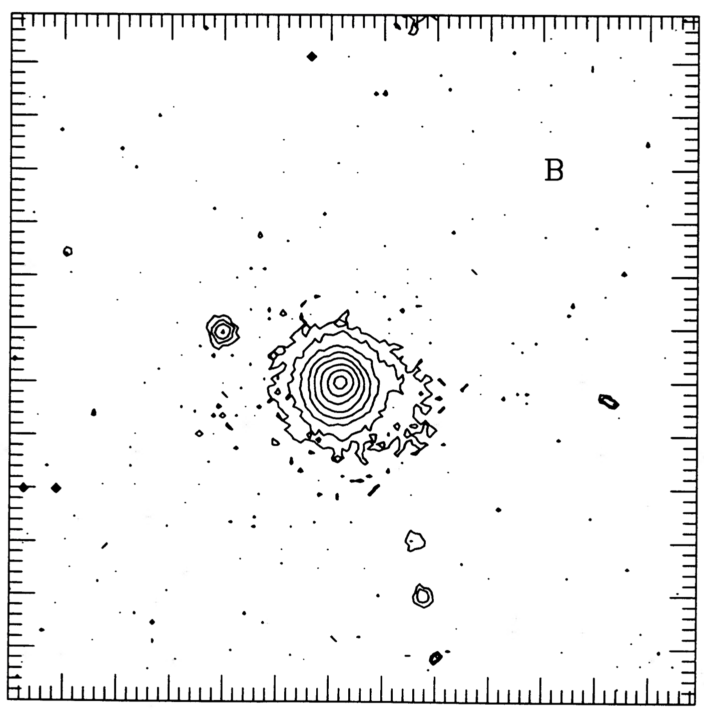

FIG. 3.—A *B* band CCD isophotal image of 0833+652, obtained with the Kitt Peak No. 1 0.9 m telescope. North is to the right, and west is up. *Small ticks*: 2″; *large ticks*: 10″. The considerable angular extent of the galaxy at low surface brightness is evident, as is the extended, spiral-like structure to the NE.

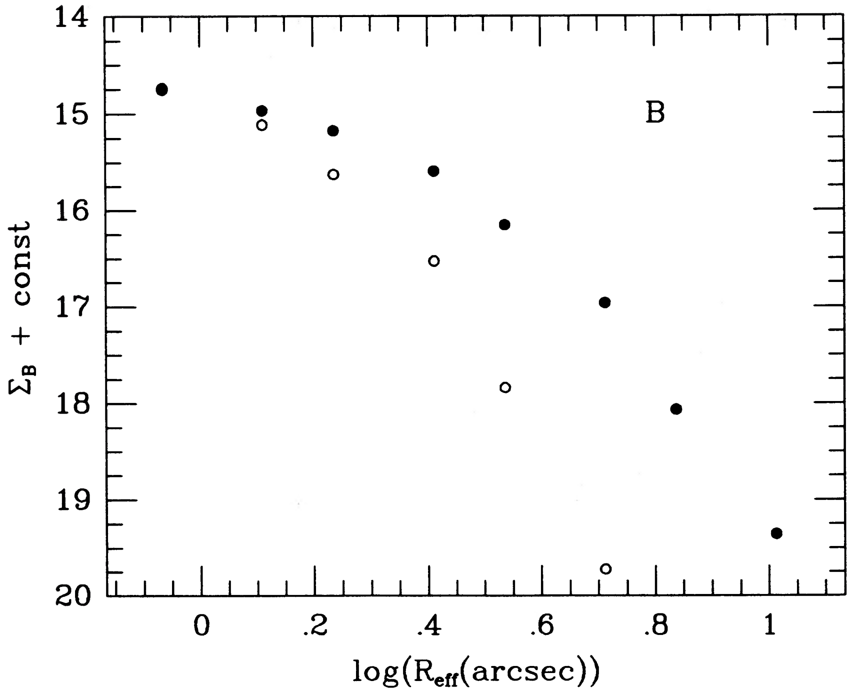

FIG. 4.—The radial dependence of the surface brightness of 0833+652 (*filled circles*) and that of a nearby star (*open circles*) from the data of Fig. 3. The distinct extension of the galaxy is evident.

excellent fit to an extrapolation of the short-wavelength end of our visible spectrophotometry, lending some credence to the calibration of both spectra, although the agreement must be regarded with caution, as the apertures of the ground-based and UV data are quite different.

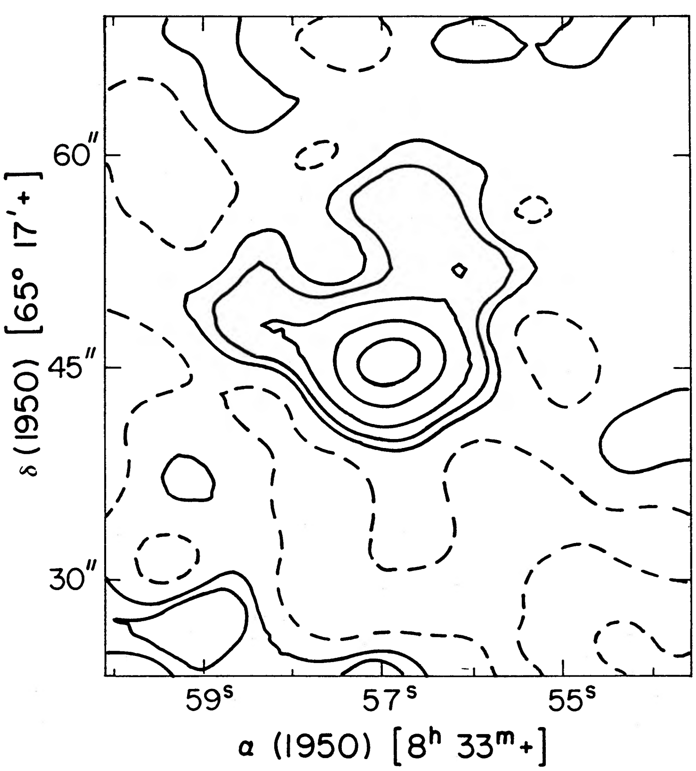

FIG. 5.—A 4.9 GHz map of the region of 0833+652, made with the Very Large Array. The observed centroid of the radio emission corresponds well with the position of the optical image.

Our measured Lyα intensity is of some interest, as these data are rare for starburst nuclei: in the otherwise well-observed cases of NGC 7714 and NGC 2782, the considerably lower redshifts leave Lyα blended with the enormously strong geocoronal line at the spectral resolution of existing *IUE* data. We adopt our value of $E(B-V) = 0.55$ derived from the visible spectrophotometry, and employ the ultraviolet extinction of Seaton (1979), although of course galactic data do indicate there can be considerable dispersion about the mean Lyα extinction as a function of line of sight (e.g., Bless and Savage 1972). Our decrement so derived, Lyα/Hβ = 23, is precisely the expected case B value. While this excellent level of agreement is surely fortuitous, it lends further confidence to our absolute flux calibration and extinction estimates, and indicates that the enhancements in predicted Lyα/Hβ decrements applicable to certain active galactic nuclei (Netzer 1982) are probably not a factor here, nor are the anomalously low decrements commonly observed in QSOs (Baldwin 1977).

e) X-Ray Observations

By construction of our grism plate sample (Anderson and Margon 1987), all fields were also observed at X-ray wavelengths at high sensitivity by the *Einstein Observatory*. The imaging proportional counter (IPC) aboard *Einstein* serendipitously detected a spatially unresolved X-ray source at a position consistent with that of 0833+652, at a significance of $\sim 4\,\sigma$ above the background, during IPC sequence number 6964, a 14,200 s exposure. The intensity of the source is 1.3×10^{-13} ergs cm^{-2} s^{-1} in the 0.5–3 keV band, for an assumed X-ray spectral index $\alpha_x = 0.5$; although there are insufficient counts detected to obtain useful X-ray spectral information, an assumption of a considerably steeper index

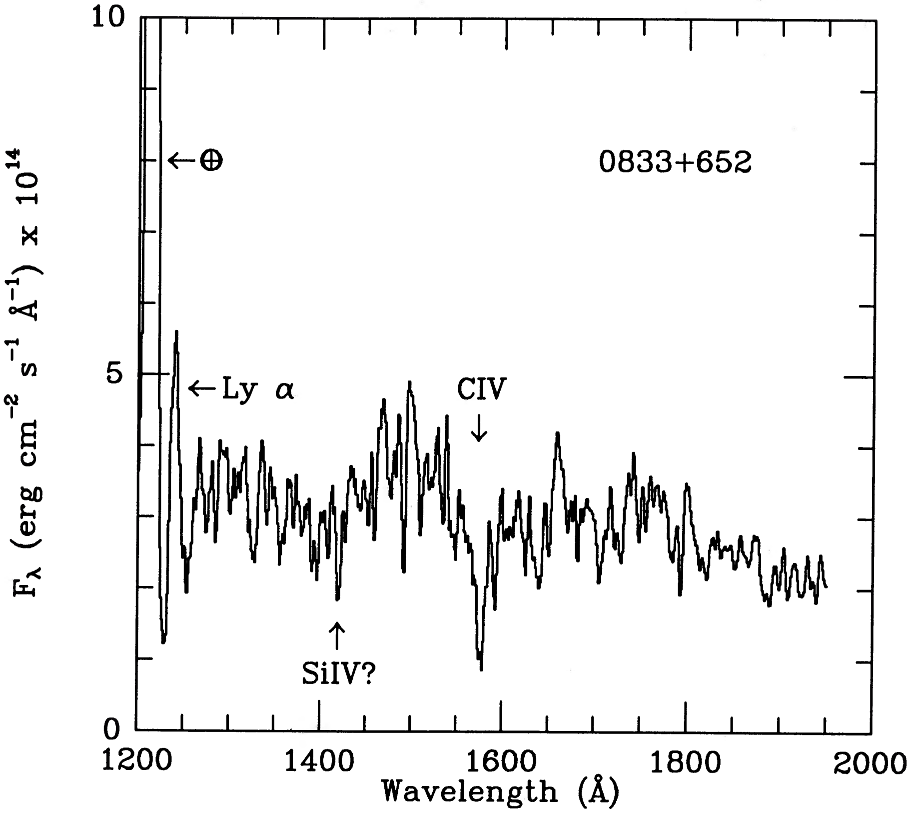

FIG. 6.—The ultraviolet spectrum of 0833 + 652, obtained with the *International Ultraviolet Explorer* (exposure SWP 26088). The reduced data have been smoothed with a three-point polynomial fit. The strong geocoronal Lyα line is marked, but the redshift of the object is sufficient to enable unambiguous resolution of Lyα emission in the galaxy as well.

would change this value by less than 10%. The probability of a chance coincidence in the IPC 1′ positional error box of an unrelated X-ray source of this flux with an object as prominent as 0833 + 652 is very small, and we therefore identify the source of X-rays with the galaxy. The infrared X-ray luminosity, including a correction for galactic interstellar absorption appropriate for this galactic latitude (a 7% effect), is 1.0×10^{41} ergs s^{-1}, again very similar to values reported in this bandpass for NGC 7714 (Weedman *et al.* 1981) and NGC 2782 (Kinney *et al.* 1984). Our observed ratio of X-ray to blue-light flux densities, $f_x/f_b = 2.3 \times 10^{-6}$, defined in the units of Fabbiano, Feigelson, and Zamorani (1982), is consistent with the correlation of these two quantities by those authors for a sample of "peculiar blue" galaxies.

III. DISCUSSION

Huchra (1987) has recently reviewed observations of star-forming galaxies and suggests that they may be empirically divided into three groups: extragalactic H II regions, clumpy irregulars, and starburst galaxies. Our data on 0833 + 652 agree remarkably well with the characteristics he suggests for starburst galaxies. The object is highly luminous, star formation is not confined to the nucleus, there is evidence for spiral structure, $F(60\ \mu m) \sim F(100\ \mu m)$, and there is a flat ultraviolet continuum with prominent absorption lines. An area where 0833 + 652 is distinctive, however, is that many or most starburst galaxies are clearly interacting with massive neighbors, while this object is apparently isolated. Assuming that a low-luminosity companion is not obscured by the object itself, 0833 + 652 may prove an interesting case for further study, to understand the trigger(s) of the starburst phenomenon in these isolated cases.

In Figure 7 we display the spectrum of 0833 + 652 over the eight decades of frequency described above in § II. There are very few starburst nuclei for which such comprehensive data are available, the most prominent examples of which we are aware being NGC 7714 and NGC 2782, as cited previously. One is struck immediately by the remarkable continuity of flux in 0833 + 652 from the infrared through the ultraviolet, with a single power law providing a reasonable fit to the continuum over a frequency range of $\sim 10^3$. A similar situation is true of NGC 7714. However, given the prominence of the Mg *b* band in the visible spectrum of 0833 + 652, presumably due to solar-type stars, this agreement must be at least partially fortuitous. Such late stars are surely not responsible for the bulk of the ultraviolet continuum, for example, where the strong C IV absorption originates from the young stellar population.

There seems little question that photoionization by hot stars is responsible for the visible emission spectrum of 0833 + 652, as our observed line ratios fit well with the published correlations for H II region-type galaxies (Baldwin, Phillips, and Terlevich 1981; Terlevich and Melnick 1985; Bushouse 1986). A further analysis of physical conditions and abundances in the emission-line region would be straightforward, but is frustrated by the modest signal-to-noise of our spectrophotometry, which was obtained primarily with the goal of merely classifying the object. We cannot measure [O III] λ4363 emission, the primary T_e diagnostic, nor [O II] λ7324, sometimes used as a secondary indicator, although the positive detections of these features in NGC 7714 by French (1980) and van Breugel *et al.* (1985) imply an expected intensity in 0833+652 which should be readily attainable through further observations. Observed strengths of [O III] and [N II] are empirically correlated with electron temperature in these galaxies (French 1980), and the similarity of these line strengths in 0833+652 and NGC 7714 suggests a similar T_e value, estimated by French as $T_e = 9000$ K in the latter case. Although we do not resolve the ultraviolet [O II] doublet, our observed [S II] $\lambda\lambda$6716, 6731 ratio implies an electron density very close to 10^3 (Osterbrock 1974), again in agreement with inferences for NGC 7714 (French 1980; Weedman *et al.* 1981). Our detections of the He I singlets are too marginal for a reasonable abundance analysis, but again could readily be improved upon. An accurate metal-abundance determination for this object would be of special interest, as inverse correlations of integrated X-ray luminosity with Z have been discussed (Clark *et al.* 1978; Bookbinder *et al.* 1980; Stewart *et al.* 1982).

Assuming that the ionization is due to hot stars, our observed Hβ flux, 2.5×10^{-13} ergs cm^{-2} s^{-1}, may be used to crudely estimate the required number of such objects. When corrected for extinction, this flux implies (Osterbrock 1974) $\sim 2.3 \times 10^{54}$ ionizing photons s^{-1}. Virtually independent of temperature, the hottest O stars supply $\sim 6.3 \times 10^{43}$ s^{-1} $L_\odot^{-1}$ (Massey 1985). Thus a population of 4×10^4 O5 stars, each of $L_{bol} \sim 10^6$ $L_\odot$, could supply the requisite flux. The strength of the ultraviolet continuum we observe in 0833+652, which must originate largely from early-type stars due to the prominent absorption, provides a consistency check. When corrected for extinction, the monochromatic UV continuum luminosity of the object is $\sim 1.7 \times 10^{42}$ ergs s^{-1} Å^{-1}. The *IUE* Spectral Atlas (Heck *et al.* 1984) indicates that a typical O5 star has monochromatic luminosity 6×10^{35} ergs s^{-1} Å^{-1} at these wavelengths, implying a population of 3×10^6 such objects in 0833+652, more than ample to provide the ionization inferred above.

The origin of the relatively powerful X-ray emission from starburst nuclei is still perplexing, and the resolution of the question may have impact on diverse problems, including the source of the diffuse X-ray background radiation at soft wavelengths (Weedman 1986). Weedman *et al.* (1981) have suggested that an extraordinarily high supernova rate (1 yr^{-1}) in the nucleus of NGC 7714 may explain the X-ray luminosity of that object. Stewart *et al.* (1982), Fabbiano, Feigelson, and Zamorani (1982), Fabbiano and Panagia (1983), and Ward (1988) invoke a population of massive X-ray binaries to explain the very high X-ray luminosity of other starburst galaxies. In some cases, the integrated X-ray emission of a large number of individual OB stars may provide yet another viable explanation (Moorwood and Glass 1982; Fabbiano and Panagia 1983). Our estimate above of the number of O stars present in

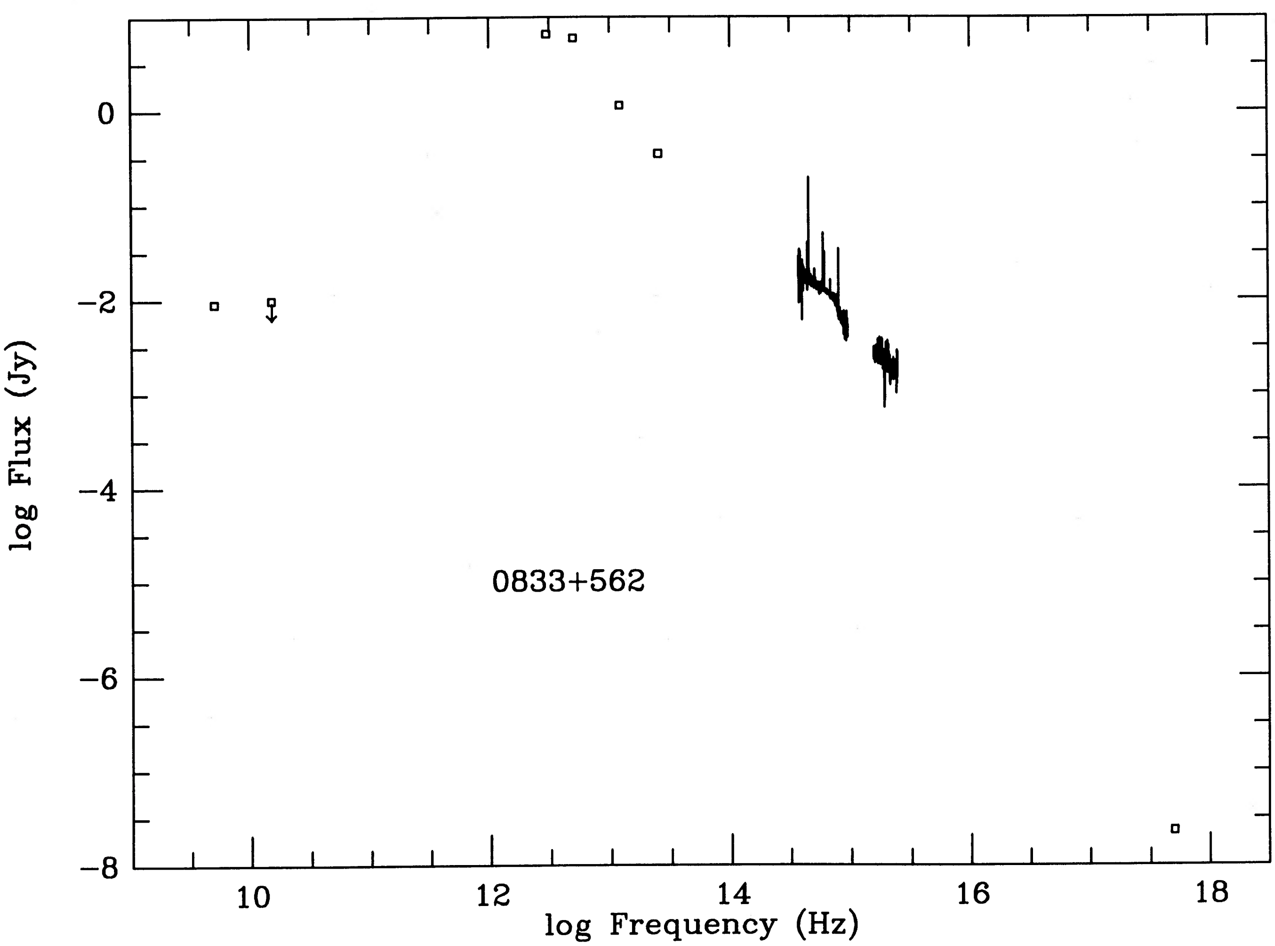

FIG. 7.—The integrated spectrum of 0833+652, including the radio, infrared, optical, ultraviolet, and X-ray data presented in the text

the object discussed here probably rules out this final model for the specific case of this galaxy, but the remaining hypotheses have implications which could be checked through further observation of 0833 + 652 and the handful of other bright, well-studied galaxies of this type. Weedman *et al.* (1981) point out that the individual supernova events may be optically detectable even in the nucleus of the galaxy; thus if more than one or two such high X-ray luminosity objects were patrolled regularly, an event rate of 1 yr^{-1} could be detected rather rapidly. A proportionally large population of early-type X-ray binaries might be identifiable through the Wolf-Rayet C, N $\lambda\lambda$4640, 4650 emission features superposed on the integrated nuclear spectrum. Van Breugel *et al.* (1985) report the possible detection of these features in Minkowski's object, and an even weaker detection in NGC 7714. Our existing blue spectrophotometry in this wavelength region is of insufficient quality to reveal these features, if present, but these data could easily be improved.

Finally, the fact that more than one or two odd examples of the starburst phenomenon prove to have relatively strong X-ray emission leads readily to the conclusion that, as with a variety of other active galaxy phenomenon, we may expect deeper X-ray surveys to provide an X-ray selected set of previously uncataloged starburst nuclei.

One of us (B. M.) is grateful for the hospitality and facilities of the Anglo-Australian Observatory, where much of this analysis was completed. We thank J. Barnes for aid in data reduction, and W. Bidelman for searching his catalogs for previous mentions of this object. This work has been supported in part by NASA grants NAG5-342, NAG8-590, and NSG8-433. The University of Washington image processing system used for reduction of portions of these data was supported by NSF grant AST 83-10552.

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Note added in proof.—In observations contemporaneous with those reported here, B. T. Soifer *et al.* (*Ap. J.*, **320**, 238 [1987]) have also identified the *IRAS* source with this galaxy and provided a redshift compatible with that we report. We are grateful to Dr. Soifer for pointing out this work and regret not citing it within the text.

Scott F. Anderson and Mario Mateo: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101-1292

Michel Fich: Department of Physics, University of Waterloo, Waterloo, ON N2L 3G1, Canada

Bruce Margon: Department of Astronomy, FM-20, University of Washington, Seattle, WA 98195

Philip Massey: Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726-6732