MARKARIAN 490: A HIGH-IONIZATION STARBURST GALAXY*

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ABSTRACT

Spectra of the galaxy Mrk 490 are described. Three components of this object may be recognized: A, the nucleus of the galaxy; B, probably a luminous H II region complex close to it; and C, either a more distant H II region or the nucleus of a smaller galaxy physically related to A. All have high-ionization emission-line spectra indicating photoionization by early-type stars. Component C has especially high ionization, and large equivalent width of Hβ, indicating a population unusually rich in very hot stars.

Key words: galaxies: starburst–galaxies: individual

I. Introduction

Markarian 490 is an interesting emission-line galaxy that was called to our attention by Nicholas Sanduleak, Warner and Swasey Observatory. In the discovery paper by Markarian and Lipovetsky (1972) and in the follow-up spectroscopy by Arakelian, Dibai, and Esipov (1973), it is described as a simple spherical system with strong Hα emission, plus other weaker emission lines. However, Sanduleak (1985, private communication) noted on a Case objective-prism plate "what appear to be two components (A and B) in the main body, as well as a third source of emission, C, located about 10" to the north. The three sources vary widely in excitation with C being of exceptionally high excitation."

This same galaxy was also found in the Palomar-Green survey as PG 1544+461, an ultraviolet-excess extragalactic object with a "dominant starlike appearance," but "with narrow emission lines, such as those observed in Seyfert 2 galaxies." It therefore is not included in the Palomar Bright Quasar Survey (Schmidt and Green 1983), but it is in the Palomar-Green Catalog (Green, Schmidt, and Liebert 1986).

Its identification in this survey was independently communicated to us by M. Schmidt and R. F. Green after we had first observed it at Dr. Sanduleak's suggestion, as part of a continuing program of investigating galaxies with strong narrow-emission lines.

II. Observations and Reductions

All our spectral data were obtained with the CCD transmission (grism) spectrograph (Lauer et al. 1984) at the Cassegrain focus of the Shane 3-m reflecting telescope of Lick Observatory. We obtained three long-slit spectra of Mrk 490 (in various orientations) with a 420-line mm⁻¹ grism in August 1985, and one with a 600-line mm⁻¹ grism in September 1985. The August spectra were taken with an 800 × 800 pixel TI chip and cover the spectral region λλ4500–8000 at a resolution of about 12 Å, while the September spectra were taken with a 500 × 500 pixel TI chip, and cover the spectral region λλ6200–7600 at a resolution of about 5.5 Å. These spectra were taken, calibrated, reduced, and measured by essentially the same procedures described in our earlier paper (Osterbrock and De Robertis 1985).
Two narrow-band and two broad-band interference-filter direct images were taken of Mrk 490 with the same Cassegrain instrument in the direct mode. The narrow-band filter used has a central wavelength of 5000 Å, full width at half maximum (FWHM) of 100 Å, and peak transmission of about 60%; while the broad-band filter has the same central wavelength and transmission efficiency, but a FWHM of about 700 Å. The approximate spatial scale in both images is 0.7' pixel$^{-1}$. The data are slightly underresolved since seeing conditions were about 1", as defined by the FWHMs of the point-spread functions of stars recorded on the same images. For each filter, the raw images were divided by the appropriate flat field using the twilight sky, aligned, coadded, and finally sky subtracted to produce a single reduced image. For components A and B, the narrow-band image is dominated by the emission lines, while the broad-band image is dominated by the continuum radiation.

III. Spectra

As the direct images discussed below show, the central object is elongated, and can be approximately divided into two "point sources", the main central object A plus the "second component" of the central object B, separated from it by about 3' to 3.5'. The heliocentric redshift of A + B, measured from our spectra, is $z = 0.0086 \pm 0.0002$. Its spectrum is shown in Figure 1. The "third source" C is very well resolved, 12" distant from A. Its redshift is slightly but significantly larger, $z(A + B) - z(C) = -0.0002 \pm 0.0002$. Its spectrum is shown in Figure 2.

From these spectra we measured the relative intensities of A + B together, of A alone (less accurately than the sum), and of C alone as given in Table I. The Hα [N II] complex λ6548, 6563, 6583 and the [S II] doublet λ6716, 6731 could only be resolved on the higher-dispersion spectra, and the ratios within each of the groups come from them alone. The high-dispersion spectra of A + B and of C are shown separately in Figure 3. We also list the measured absolute values of the Hα flux (in erg cm$^{-2}$ s$^{-1}$), which are considerably less accurate than the relative line intensities, for the reasons explained earlier (Osterbrock and De Robertis 1985). The probable errors of the mean listed in Table I are determined from the internal consistency of the two independent determinations of each flux. The equivalent widths of the Hβ emission lines are also listed; they are also considerably more accurate than the fluxes alone.

The line widths of the stronger emission lines were also measured, following the standard methods outlined by Osterbrock and De Robertis (1985). Briefly, the FWHMs were measured for Mrk 490 as observed and for the comparison lines of Ne I, C II, and He I. The latter were taken to represent the instrumental profile. From them the instrumental FWHM was interpolated at the position of each emission line measured in Mrk 490. This interpolation is necessary because of the variation of focus along the CCD chip. The average instrumental FWHM for the four comparison lines measured was 5.5 Å, corresponding to 225 km s$^{-1}$. The intrinsic FWHM was then calculated for each line as the square root of the difference between the squares of its measured FWHM and the interpolated instrumental FWHM. The results are listed in Table II. The [N II] measurement depends on λ6583 alone while the [S II] value comes from combining λ6716, 6731.

The emission lines are very narrow, certainly considerably narrower than the instrumental profiles. The numerical values listed, particularly 35 km s$^{-1}$, are not highly significant because the differences in illumination of the slit between the point-source objects (modified by seeing).
TABLE I

<table>
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<tr>
<th></th>
<th>A + B</th>
<th>A</th>
<th>C</th>
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<tr>
<td>Hγ</td>
<td>4340</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>[O III]</td>
<td>4363</td>
<td>0.012</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Hβ</td>
<td>4861</td>
<td>0.30</td>
<td>0.37</td>
</tr>
<tr>
<td>[O III]</td>
<td>4959</td>
<td>0.34</td>
<td>0.92</td>
</tr>
<tr>
<td>[O III]</td>
<td>5007</td>
<td>1.01</td>
<td>2.67</td>
</tr>
<tr>
<td>He I</td>
<td>5876</td>
<td>0.047</td>
<td>0.068</td>
</tr>
<tr>
<td>[O I]</td>
<td>6300</td>
<td>0.022</td>
<td>0.018</td>
</tr>
<tr>
<td>[N II]</td>
<td>6548</td>
<td>0.032</td>
<td>0.029</td>
</tr>
<tr>
<td>Hα</td>
<td>6563</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>[N II]</td>
<td>6583</td>
<td>0.097</td>
<td>0.097</td>
</tr>
<tr>
<td>He I</td>
<td>6678</td>
<td>0.011</td>
<td>0.013</td>
</tr>
<tr>
<td>[S II]</td>
<td>6716</td>
<td>0.126</td>
<td>0.137</td>
</tr>
<tr>
<td>[S II]</td>
<td>6731</td>
<td>0.092</td>
<td>0.094</td>
</tr>
<tr>
<td>[A III]</td>
<td>7135</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[O II]</td>
<td>7325</td>
<td>0.018</td>
<td>–</td>
</tr>
<tr>
<td>Hα flux</td>
<td>(10^-14)</td>
<td>16.5±4.5</td>
<td>9.0±0.8</td>
</tr>
<tr>
<td>Hβ</td>
<td>W(Å)</td>
<td>38</td>
<td>460</td>
</tr>
</tbody>
</table>

and the diffuse comparison-line sources make the quadratic sum assumption increasingly inaccurate for such narrow lines.

IV. Direct Images

From the narrow-band image, (Fig. 4) component B appears to be a point source at a position angle of –30° ± 2° relative to A. The distance between them, 3°0–3°5 as measured on this image, corresponds to about 500 pc, adopting $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. The intensity profile of A is considerably broader than the point-spread function even in the narrow-band image, suggesting that A is centered in an underlying galaxy of stars. On the broad-band image, the distinction between A and B is less clear.

Feature C is a very strong emission-line source with relatively little continuum radiation, at a position angle of 6° ± 1° with respect to A. The separation between A and C, 12°2 from an accurate fit to the intensity profiles, corresponds to a projected distance 2.0 kpc for the same value of $H_0$. The intensity profile which passes through the center of A and C reveals that there is some "excess luminosity" between A and C (at the few-percent level) in both the broad- and narrow-band images over and above the underlying galaxy centered on A plus any possible contribution from B.

We divided the aligned narrow-band and broad-band images to search for regions which have predominantly line or continuum emission. Apart from the sharp features centered directly on A, B, and C themselves, the divided image was relatively flat, except for the region between A and C in which there is a gradient increasing toward C suggesting an "excess" of emission-line material.

V. Interpretation

The emission-line spectra of A, B, and C are quite normal except for their high ionization. The reddening in
Mrk 490 $E_{B-V} \leq 0.1$ for $A + B$ or $E_{B-V} \approx 0$ for $C$, as derived from the Balmer-line ratios, is very small. In $A + B$ the [S II] $\lambda 6716/\lambda 6731$ ratio corresponds to a mean electron density $N_e = 80 \text{ cm}^{-3}$. The [O III] ($\lambda 4959 + \lambda 5007)/\lambda 4363$ intensity ratio, corrected approximately for interstellar reddening, is 119, corresponding to $T = 12,000 \text{ K}$. The He I $\lambda 5876/\text{H}\alpha$ intensity ratio, corrected for the same reddening, is 0.12, corresponding to an abundance ratio $\text{He}^+/\text{H}^+ = 0.11$.

For component C the [S II] ratio gives $N_e = 120 \text{ cm}^{-3}$, while the upper limit to the strength of $\lambda 4363$ corresponds to $T \leq 11,000 \text{ K}$. The relative intensity of He I $\lambda 5876$ corresponds to $\text{He}^+/\text{H}^+ = 0.14$. The difference between this and the corresponding value for $A + B$ is probably a result of errors in our measurements of the faint lines, but may indicate that He is not ionized to $\text{He}^+$ throughout $A + B$.

As noted above, A has an H II region spectrum and is centered in a well-resolved luminosity distribution which appears to be an underlying galaxy. It is evidently the starburst nucleus of this galaxy. It is impossible to categorize features B and C unambiguously. B is probably a luminous H II region complex very near the nucleus of the galaxy dominated by A. Line ratios, equivalent widths, and direct images substantiate this interpretation. However, at the spatial resolution of these images it is impossible to rule out other interpretations, such as that B is a knot at the end of a “jet” issuing from A, etc.

The projected linear separation (2.0 kpc) and line-of-sight velocity difference (60 km $s^{-1}$) between A and C permit at least two reasonable interpretations for C. Either it is a very high-ionization H II region associated with the galaxy centered on A, or it is the nucleus of a smaller galaxy which is physically connected to the galaxy centered on A. In the former interpretation, the “bridge” between A and C might be a spiral arm, while in the latter it might be the remnant of a recent tidal interaction (followed by star formation) between the two galaxies. An item of evidence that strongly favors this interpretation is provided by the high-resolution, long-slit CCD spectra. The centroids of the intensity distributions of A and C as functions of wavelength show that the centroids of the emission lines in A are shifted approximately 1" relative to the continuum toward C, while the centroids of the emission lines in C are shifted by slightly less than this toward A. This effect is illustrated in Figure 5 for both A and C for H$\alpha$, [N II] $\lambda 6548, 6583$, and [S II] $\lambda 6716, 6731$. It is probably not a coincidence but an indication that A and C represent the emission-line nuclei of different galaxies which have recently interacted gravitationally.

### VI. Ionizing Radiation

The emission-line spectra shown in Figures 1, 2, and 3 and listed in Table I are clearly those of a galaxy photoionized by hot stars. The line ratios, particularly [O I] $\lambda 6300/\text{H}\alpha$, [N II] $\lambda 6583/\text{H}\alpha$, and [S II] ($\lambda 6716 + \lambda 6731)/\text{H}\alpha$ as functions of [O III] $\lambda 5007/\text{H}\beta$, all clearly show that Mrk 490 is a “starburst” or “H II region” galaxy, not a Seyfert galaxy (French 1980; Baldwin, Phillips, and Terlevich 1981; Weedman et al. 1981). Reddening hardly affects these intensity ratios since the lines are very close in wavelength.

The ionization of Mrk 490 $A + B$ (the central component), [O III] $\lambda 5007/\text{H}\beta = 3$ is fairly representative of many starburst galaxies. However, the ionization of C, $\lambda 5007/\text{H}\beta = 7.2$ is unusually high. For instance, of the 14 “H II region” galaxies studied by French (1980), only two have ionization ratios above this level (II Zw 40 with $\lambda 5007/\text{H}\beta = 8.0$ and I Zw 122 with $\lambda 5007/\text{H}\beta = 7.0$). Of the 60 generally higher-luminosity galaxies measured by Balzano (1983), only one, Mrk 193 with $\lambda 5007/\text{H}\beta = 7.9$, is comparable. Thus the ionizing radiation in Mrk 490 C must come from a population containing an unusually high fraction of high-temperature (early O-type) stars.

This is further confirmed by the very large equivalent width of $\text{H}\beta$ in Mrk 490 C, 460 Å as listed in Table I. Of the objects measured by French (1980), this is approached only by II Zw 40 with $W(\text{H}\beta) = 300$ Å. Balzano (1983) does not list equivalent widths. Among the 99 giant H II regions in external galaxies measured by McCaill, Rubski, and Shields (1985), the two with the largest $\text{H}\beta$ equivalent widths are (in their designations) NGC 5068 ($-092 +092$) with $W(\text{H}\beta) = 322$ Å and NGC 628 ($-186 +056$) with $W(\text{H}\beta) = 303$ Å.

These observed equivalent widths are expressed in
terms of the observed continuum fluxes, which contain contributions from the nebular continuum (bound-free plus free-free plus two-photon) as well as from the continuous spectra of the involved stars. The calculated equivalent width of Hβ, expressed in terms of the nebular continuum alone (in the low-density limit and with \( \text{He}^+ / \text{H}^+ = 0.12 \)) is \( W_{\text{neb}} \) (Hβ) = 1350 Å. The equivalent width \( W \), expressed in terms of the stars’ continuum alone, with the nebular continuum removed, is then given by

\[
\frac{1}{W} = \frac{1}{W_{\text{neb}}} = \frac{1}{W_{\text{neb}}}.
\]

Thus for Mrk 490 C, \( W_{\text{neb}} \) (Hβ) = 690 Å.

For comparison with theoretically calculated values we may use the model O-star atmospheres of Kurucz (1979). Following, for instance, the methods and notation outlined in Osterbrock (1974), it is easy to show that for an ionization-bounded H II region

\[
W_{\text{neb}} \text{ (Hβ)} = \frac{\alpha_{\text{Hβ}}}{\alpha_{\text{β}}} \int_0^\infty \frac{L_\lambda}{h \nu} d\nu = \frac{\alpha_{\text{Hβ}}}{\alpha_{\text{β}}} \int_0^\infty \frac{F_\lambda}{h \nu} d\nu = \frac{F_{\lambda, 4861}}{h \nu_{\text{Hβ}}}.
\]

For a density-bounded H II region from which some of the ionizing photons escape, this is an upper limit. The numerical values of the integrals have been kindly provided by R. H. Rubin for three model atmospheres believed to be representative of early-type stars, and the resulting calculated equivalent widths are listed in Table III. It can be seen that even for the hottest stars for which models have been calculated, the expected equivalent width is only 5.5 times that observed in Mrk 490 C. Real OB associations include stars covering a wide range of temperatures; only the hottest contribute appreciably to the number of ionizing photons, that is, to the strength of Hβ emission, while all the stars contribute to the optical light, that is, to diluting the Hβ equivalent width. This result shows that in Mrk 490 C there must be a population of stars whose summed optical radiation amounts only to 5.5 times that of the hottest stars, a quite small value.

A comparison may also be made with an observed H II region in our Galaxy, the close and well-studied Orion nebula. Although its total Hβ flux is not known to us to be published, the radio-frequency flux from Orion A = M 43 = NGC 1976 + NGC 1982 has been measured by Schraml and Mezger (1969) as \( F_\nu \) (15.375 GHz) = 4.00 \times 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}. This can be converted to the Hβ flux that would be observed if there were no extinction in Orion, \( F_{\text{Hβ}} = 1.69 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}. The most luminous ionizing star in the Orion nebula is HD 37022 = \theta^1 Ori C (in the standard notation of Burnham’s General Catalogue of Double Stars), an O6 star with \( V = 5.14, (B-V) = -0.38 \) (Sharpless 1952). Using for its extinction \( A_V = 1.4 \), the mean of the determinations for this star by Sharpless and for the nebula by Gebel (1968) gives for its intrinsic (corrected for reddening) apparent magnitudes \( V_0 = 3.7, B_0 = 3.3. \) From standard transformations (Code 1960) these correspond to the continuum flux from \( \theta^1 \) Ori C corrected for extinction, \( F_{\lambda, 4861} = 1.96 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}. \) This gives a calculated equivalent width from the Orion nebula, expressed in terms of the continuum of \( \theta^1 \) Ori C alone, of \( W_{\text{neb}} \) (Hβ) = 860 Å, only 25% larger than the value observed in Mrk 490 C. If only the four brightest Trapezium components \( \theta^1 \) Ori A, B, C, D, plus \( \theta^2 \) Ori, the luminous O9 III star in NGC 1982, are included, the calculated equivalent width of the nebular emission line drops to \( W_{\text{neb}} \) (Hβ) = 300 Å, smaller than observed in Mrk 490 C. Clearly in Orion many more B stars than this actually contribute to the stellar continuum luminosity at 4861 but not appreciably to the photoionization, further diluting the equivalent width. In fact if all the stars measured by Sharpless (1952) in the Orion ag-

<table>
<thead>
<tr>
<th>T</th>
<th>log g</th>
<th>W</th>
</tr>
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<tr>
<td>45000</td>
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<td>40000</td>
<td>4.0</td>
<td>2260</td>
</tr>
<tr>
<td>35000</td>
<td>3.5</td>
<td>1260</td>
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</tbody>
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aggregate, approximately 13° in diameter (which would be reduced to 0.7 at the distance of Mrk 490), are included, the calculated emission-line equivalent width is \( W(\text{H}\beta) \approx W(\text{H}\beta) \approx 9 \text{ Å} \). The population in Mrk 490 C obviously contains a much higher proportion of very early-type stars than the population in Orion.

It is of course possible to imagine geometries in which dust inside Mrk 490 C absorbs most of the continuum radiation from the stars that is directed toward the Earth, but does not absorb much of their ultraviolet radiation that ionizes the gas around them. This interpretation is highly special and thus seems unlikely. Also, it seems even more unlikely that the stars in A (or A and B) ionize the gas in C, for the latter subtends at most about \( \pi/5 \), projected on the sky, at A, and hence presumably at most 0.03 of the total solid angle \( 4\pi \) at A. Thus it is difficult to avoid the conclusion that there is a population containing a high proportion of very early-type stars in Mrk 490 C.

We are most grateful to N. Sanduleak for calling this interesting object to our attention, to M. Schmidt and R. F. Green for sending us their unpublished list of narrow-line PG objects, and to R. H. Rubin for providing us with the numerical values of integrated fluxes of ionizing photons in the Kurucz models. We are also indebted to S. Veilleux, R. A. Shaw, and M. L. McCall for numerous discussions on the topic of this paper, and to the National Science Foundation for partial support of this research under grant AST 83-11585.

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