OPTICAL SPECTRA OF RADIO AND SEYFERT GALAXIES*

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I was very glad to have the opportunity of participating in this symposium, for I knew Rudolph Minkowski well, and worked closely with him during my five years at Caltech. He was my guide, mentor, and friend, whom I always found most generous and helpful, particularly in all kinds of spectroscopic problems connected with nebulae and galaxies. After I left Pasadena for Wisconsin, we wrote two joint papers by correspondence, and after he retired from the Hale Observatories he spent one year as a Visiting Professor in Madison, actually in my position while I was on leave at Princeton. During this period we jointly supervised C. R. O'Dell's Ph.D. thesis on the properties and evolution of planetary nebulae and their central stars, another topic to which Rudolph made many contributions.

At Lick Observatory we are now carrying out a spectrophotometric survey of radio galaxies with emission lines in their spectra, using the image-tube image-dissector scanner to measure the lines and continuous spectra of a large number of these objects. Some of this work has been published, other parts are in press, while much of it is still in progress. Participants in various parts of the program have included J. S. Miller, R. Costero, A. T. Koski, M. M. Phillips, S. A. Hawley, J. E. Tohline, and S. A. Grandi.

Cygnus A, one of the first identifications made by Baade and Minkowski, is the archotypical narrow-line radio galaxy, with emission lines showing a wide range of ionization, from [O I], [N I], and [S II] to [Ne V], [Fe II], and [Fe X], all with widths of approximately 500 km sec⁻¹. The H I emission-line intensities fit calculated recombination relative intensities if we assume interstellar extinction corresponding to $E_B - V = 0.7$, probably much of it internal. No absorption lines are seen in the continuum of this galaxy. There is general agreement of the measured line intensities with photoionization models calculated by MacAlpine, assuming approximately normal abundances of the elements and a power-law input spectrum of ionizing radiation, $F_\nu \propto \nu^{-n}$ with $n = 1.6$. In particular, the [O III] ($\lambda 4959 + \lambda 5007$)/$\lambda 4363$ ratio corresponds to $T \approx 15,000^\circ$ K, consistent with photoionization energy input but contradicting shock-wave input models.

Approximately 20 other radio galaxies with emission lines in their spectra have been observed in this program to date. Roughly three-quarters of them have narrow emission lines generally similar to those of Cyg A. In the five narrow-line radio-galaxy spectral scans reduced to date absorption lines are seen, but with smaller equivalent widths than in typically normal galaxies. The emission-line spectrum can be approximately corrected for extinction from the H I lines, but this extinction does not fit the observed continuum, probably indicating that the ionized gas and dust are more condensed than the stellar distribution. All these galaxies have strong [O I] and [S II]; three of them have high-ionization spectra similar to Cyg A while in the other two [O III] and [Ne III] are weaker and [O II] and [N II] are stronger. It appears likely that photoionization models will fit these objects, but models calculated with a range of exponents are needed to test this hypothesis.

Five of the radio galaxies observed have broad H I emission lines and narrow forbidden lines in their spectra. Four of them, 3C 382, 3C 390.3, 3C 327, and 3C 445 have weak absorption lines and approximate power-law continua. The broad Balmer lines have considerable structure, indicating that mass motions are the main broadening mechanism. The broad H I components have a steeper decrement than the sharp cores, which have the same redshifts and profiles as the forbidden lines. In the narrow-line emitting regions $N_e = 10^6$ or $10^7$ cm⁻³, while in the broad-line regions $N_e \geq 10^9$ cm⁻³. The masses of ionized gas in the broad-line regions are of order $10^{-2}$ $M_\odot$, while the sizes may be of order $10^{-2}$ pc. Significant variations of the profiles of the broad H β and Hγ in 3C 390.3 have been measured in a time of one year.

Spectrophotometry of Seyfert galaxies has also been undertaken because of the similarity of their emission-line spectra to the emission-line spectra of radio galaxies. About one-fourth of the Seyfert galaxies are narrow-line objects belonging to the Seyfert 2 group in the classification scheme of Khachikian and Weedman. These objects and the apparently very similar narrow-line radio galaxies are being studied by A. T. Koski.

*A summary of one of the invited papers presented at the Rudolph Minkowski Symposium, A.S.P. Summer Meeting, Berkeley, 18–22 May 1976.
Among the broad-line Seyfert 1 galaxies, approximately 45 have been scanned, reduced to energy units, and classified to date. Of these, quantitative line and continuum measurements were completed for 14 by the end of 1975 and form the basis for the following summary. There is a wide range in widths of the H\textsc{i} lines in Seyfert 1 galaxies, from 6000 km sec\(^{-1}\) to about 15,000 km sec\(^{-1}\), and many of them are asymmetric, with the peak to the violet of the center of the wings. Nearly all Seyfert 1 galaxies show the Fe\textsc{ii} blends \(\lambda 4570\), \(\lambda 5190\), and \(\lambda 5320\) in emission, with a wide range in strength from one object to another. The H\textalpha/H\beta/H\gamma ratios do not agree with recombination plus interstellar extinction, and are probably strongly affected by self-absorption and collisional excitation in the dense regions in which the broad H\textsc{i}, He\textsc{i}, and He\textsc{ii} lines are emitted. There is strong evidence for self-absorption in He\textsc{i} also. The He\textsc{ii}/H\textsc{i} ratio falls within a relatively narrow range, but the He\textsc{ii}/H\textsc{i} ratio varies widely from object to object. The level of ionization observed in a particular galaxy is not strongly correlated with the widths of its emission-line profiles. Though the concept of the two classes, Seyfert 1 and Seyfert 2, is a good one, there are intermediate objects such as NGC 4151 and Mk 6, so evidently the relative proportion of broad- and narrow-line emitting regions varies continuously. The narrow-line spectra of Seyfert 1 galaxies are very similar to the spectra of Seyfert 2 galaxies and narrow-line radio galaxies. The broad-line regions are much denser and are probably something like stellar chromospheres. The broadening is due to mass motions, which may include rotation, expansion, and turbulence.

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