OBSERVATIONAL RESULTS ON SEYFERT AND RADIO GALAXIES WITH THE LICK OBSERVATORY IMAGE TUBE-IMAGE DISSECTOR SCANNER

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ABSTRACT

The Lick Observatory image tube-image dissector spectral scanner is described, emphasizing the ways in which it has been optimized for production of research results by a relatively small group of astronomers who use it frequently. A survey of optical spectra of radio and Seyfert galaxies made with this instrument is described, and some of the main results to date are summarized. An observational model of an active galaxy nucleus, in which irregular expansion of ionized gas occurs in a plane, is suggested. Recent optical spectra of OQ 208 = Mrk 668, a broad-line radio galaxy with a large redshift difference between its broad and narrow emission lines, are described and tentatively interpreted.

RESUMEN

Se describe el tubo de imágenes-dissector de imágenes del Observatorio de Lick enfatizando la forma en que ha sido optimizado para producir resultados de investigación al ser usado con frecuencia por un grupo relativamente pequeño de astrónomos. Se describe un examen sistemático de los espectros ópticos de radiogalaxias y galaxias Seyfert que se ha hecho con este instrumento, y se resumen los resultados más importantes hasta la fecha. Se propone un modelo observacional para un núcleo galáctico activo, modelo en el cual el gas ionizado se expande irregularmente en un plano. Se describen y se interpretan en forma tentativa los recientes espectros ópticos de OQ 208 = Mrk 668, una radio-galaxia de líneas anchas con una gran diferencia entre los corrimientos al rojo de las líneas de emisión anchas y los de las angostas.

Me da mucho gusto estar aquí, en este país tan bello, con mis amigos tan agradables, y tener la oportunidad de participar en la inauguración de las nuevas instalaciones del Observatorio Astronómico Nacional en San Pedro Mártir. Todos conocemos las muchas contribuciones importantes de los astrónomos mexicanos —las de los Drs. Guillermo Haro, Arcadio Poveda, Manuel Peimbert, y de muchos otros. Estoy seguro que este Observatorio les permitirá entrar en una era nueva de descubrimientos astronómicos. ¡Uds. tienen todos nuestros mejores deseos!

The Lick Observatory image-tube image-dissector system was a very advanced instrument when it was introduced by Robinson and Wampler (1972). It is a spectral scanner which combines high efficiency, multiplexing in wavelength, and digital readout. Today few people would say that it is the wave of the future, but it has produced and is still producing a lot of important results. These include among others the largest published redshift for a quasar, $z = 3.53$ in OQ 172 by Wampler, Robinson, Burbidge and Baldwin (1973), and the largest published redshift for an emission-line radio galaxy, $z = 0.840$ in 3C 6.1 by Smith et al. (1979). I had nothing to do with designing or building this highly effective system and I therefore hope I can be forgiven for boasting a little about it. Our experience with it may be useful in planning other instruments for the future.

The Wampler-Robinson image-tube image-dissector system was first put into use on the Shane 3-m reflector with an available spectrograph. A new spectrograph matched to the system was built in the Lick Observatory shops under Miller’s supervision and went into operation in 1974 (Miller, Robinson and Wampler, 1976). Its grating tray holds three gratings which are thus available almost immediately under remote operation, which also controls the two Schmidt correctors, the slit width and length, the grating tilt, and the focus of the
collimator. Thus it is possible to change the spectral settings rapidly in a completely reproducible way. A lot of thought went into making this system highly user-oriented. An array of switches makes it possible to call and operate the programs needed in taking data during the night. Only minimum communication through a Decwriter is necessary, and all the commands are simple enough so that even a very sleepy astronomer can almost always type them correctly. The Lick Observatory image-tube image-dissector scanner is a production instrument used by about twenty astronomers from the University of California system, each of whom works with it several times a year and is thus highly familiar with it. This is probably much like the situation that will occur with the new 2.12-m telescope at San Pedro Mártir. During the past several years about sixty to sixty-five percent of the observing time on the Shane 3-m telescope at Lick Observatory has been devoted to observations with the image-tube image-dissector system.

The data-taking and reduction programs have been very highly developed under the supervision of L.B. Robinson, J.S. Miller, R. Kibbrick, and J. Baldwin. Many graduate students and postdoctoral research fellows have participated in writing and modifying these programs. A telescope-pointing program developed by D.M. Rank, L.B. Robinson, and J. Osborne permits the telescope, completed and put into operation back in 1959, to be pointed to an object with known coordinates anywhere in the sky to within a few seconds of arc. This plus an automatic slit-changing program, which shifts the object being observed from one slit to the other at the end of each exposure, greatly speeds up the data taking. Our philosophy has been to keep improving programs and procedures that work, and not to discard methods in use until we are sure that others are better and that we can afford them both in money and in person-power. As a result we are still using PDP 8 computers to control the scanner and its data-taking, because we have a large investment in software developed for them. However most of the batch reduction of the scanner data is done on various large IBM computers on the several University of California campuses.

With this scanner we find we can routinely do reproducible spectrophotometry to an accuracy of ten percent or better. The reduction to energy units is provided from a network of secondary standard stars with magnitudes $m \approx 10$ to 12, about the brightest stars that can be observed with this system without a neutral density filter. These standards were measured in energy units by Stone (1974, 1977) using the one-channel original Wampler scanner unit on the Crossley reflector. We take comparison spectra of Ne, He, Hg and Ar gas tubes at the beginning and end of the night, usually with the telescope in the vertical position, but to eliminate the effects of flexure the zero-point of wavelength for each scan is determined from emission lines in the sky spectrum recorded simultaneously with the spectra of the object being observed. With this instrument good spectral photometric scans can be obtained of galaxies in the range $m \approx 14.5$ to 18 in reasonable exposure times ranging up to 64 minutes.

Lick Observatory is a very good site for observational astronomy. Long-term statistics over the years 1965 to 1974 show that on the average we are able to work nearly nine hours per night in the best months of the year, August and September. During this season the seeing is also at its best on Mount Hamilton. The worst season is December through April, when we are able to work on the average about 5 hours per night. Most of this observing comes in blocks of more than 5 hours, with one or more cloudy nights between clear periods. The seeing is also worse in the winter than in the good observing season in late summer and early fall. In my own program data are actually being taken during about 85 percent of the observing time, and only about 15 percent of the time is used for moving the telescope, identifying the field, and changing the object from one slit to the other.

The main problem with the Mount Hamilton site of Lick Observatory is the increasing light pollution from San José and other communities in the Santa Clara Valley. At the present time the average level of sky brightness when the moon is down is about three times that at a dark-sky site (Walker, 1973). That is, about two-thirds of the sky brightness at Mount Hamilton is due to artificial light sources, scattered back into the telescope by the atmosphere above the Observatory, while about one-third is the natural emission spec-
trum of the night sky plus unresolved stars and galaxies. The main emission lines of the light pollution spectrum are due to Hg I from mercury vapor lamps and there is also a continuum, presumably mostly due to automobile headlights plus light escaping from windows of houses (Osterbrock, Walker and Koski, 1976).

At the present time our sky subtraction techniques are highly effective, but the danger is that light pollution may continue to increase. We are working with governing bodies and lighting departments in an effort to slow the rate of light pollution and to channel it into the astronomically most favorable form of low-pressure sodium lamps, which emit almost entirely in a few monochromatic lines. The astronomically worst type of lights are high-pressure sodium, which emit radiation at practically all wavelengths in the region longward of 5500 Å.

Next I would like to talk briefly about the survey of Seyfert and radio galaxies with emission lines in their spectra which I have been making with this instrument. The survey is still going on but in the past six years many spectra have been obtained and some conclusions have been reached (Osterbrock, 1978). I will briefly summarize the results and give examples from the Lick Observatory work with which I am most familiar although of course much other research at other observatories has contributed to our understanding of these objects. A majority of the known radio galaxies with emission lines in their spectra have only narrow lines, with widths of order 500 km s\(^{-1}\), significantly wider than "normal" galaxies but much narrower than the very wide lines seen in a few radio galaxies. We call these objects narrow-line radio galaxies, and an example with very strong narrow emission lines is Cyg A. The emission-line spectra of these objects can best be fitted by photoionization models, in which the input ionization source is a power-law with slope and intensity approximately fitting the observed optical featureless continuum in these objects (Osterbrock and Miller, 1976; Koski, 1978). The abundances of the elements in the ionized gas are approximately normal. Electron densities are \(N_e \approx 10^4\) cm\(^{-3}\).

A minority of the radio-quiet Seyfert galaxies have very similar emission-line spectra. These are the galaxies called Seyfert 2 in the classification scheme of Khachikian and Weedman (1974). So far as we can tell there is no characteristic difference in the optical emission-line spectra between the narrow-line radio galaxies and the Seyfert 2 galaxies, but in morphological form most of the former are cD, D, or E galaxies, while most of the latter are spiral galaxies, to the extent they can be classified (Weedman, 1977; Grandi and Osterbrock, 1978).

A minority of the radio galaxies with emission lines in their spectra have broad H I, He I and He II lines in their spectra with full width at zero intensity up to nearly one-tenth the velocity of light. The broad lines are known from previous work to be emitted in a high-density region, with \(N_e \approx 10^{10}\) cm\(^{-3}\), so that all forbidden lines are too weak to be observed. Measurements of the Balmer decrement in these broad emission lines suggest that more than simple recombination is involved in their emission and that probably collisional, radiative, and dust effects all play a role (Osterbrock, 1977). Measurements of \(\lambda x\) from above the earth's atmosphere are adding and will add more to our knowledge of the conditions in these dense regions (Ferland et al., 1979). The radio-quiet objects with similar broad-line spectra are Seyfert 1 galaxies in the classification scheme.
of Khachikian and Weedman. These Seyfert 1 galaxies, like the Seyfert 2 galaxies, tend to be mostly spiral galaxies to the extent they can be classified. There is a wide range in velocity width from one broad-line object to another, the extremes of the full width at zero intensity ranging from about 3000 km s\(^{-1}\) to about 30 000 km s\(^{-1}\). Some Seyfert 1 galaxies show a high level of ionization, up to [Fe X] and [Fe XI] (Grandidié, 1978), indicating the presence of photons with energies well above the 250-volt ionization limit necessary to produce these ions.

Many of these emission-line galaxies have H I profiles that are composite, with a strong broad component plus a strong narrow component with very nearly the same redshift and width as the narrow lines. Such an object might be called a Seyfert 1.5 galaxy, and all combinations of dense broad-line regions with lower density narrow-line regions seem to exist (Osterbrock, 1977). Nearly all bright Seyfert 1 galaxies have been detected as X-ray sources (Elvis et al., 1978; Tananbaum et al., 1978). A very few X-ray galaxies appear to have only narrow emission lines, but Dr. J.M. Shuder, working with me at Lick Observatory, has been able to find a very weak broad component of H I in nearly every one of these galaxies.

Some general results are that nearly all radio galaxies with emission lines have strong narrow lines. That is, the broad-line radio galaxies actually have spectra more like Seyfert 1.5 galaxies than Seyfert 1 galaxies and in general there is a strong correlation between the radio-emission property and the strength of narrow emission lines in the spectra. Also the broad-line radio galaxies as a group tend to have weak Fe II emission in contrast to the typical radio-quiet Seyfert 1 galaxies. This correlation is not understood on physical grounds but must give information on the physical structure of radio galaxies and of radio-quiet Seyfert galaxies (Grandidié and Osterbrock, 1978).

Light variations have been observed in the nuclei of several Seyfert 1 and broad-line radio galaxies, and variations in the broad emission-line profiles have been detected in several of these objects. This, together with the luminosity and density estimates, indicates that the dimension of the dense broad-line emitting gas is small, of order 0.1 pc. The narrow-line gas on the other hand is distributed over a much larger volume with diameter perhaps 100 to 1000 pc. The broadening of the dense-gas emission-line spectrum must be due to internal velocities. The wide range of widths suggests that some sort of orientation effect is involved, and I have sketched a specific model that fits many of the observational data, including the correlation between strong narrow optical emission lines and radio emission (Osterbrock, 1978). In this model the dense gas is distributed in clumps within a cylindrical volume with thickness smaller than its diameter, so that both ionizing photons from the central radiation source and relativistic electrons responsible for the radio emission can preferentially escape along the axis. In this model rotation and turbulence were originally suggested as the two velocity line-broadening mechanism. However rotational models do not fit well with the observed profiles (Shields, 1978).

There is a strong correlation of the strength of the broad H I emission lines (but not their widths) with the strength of the featureless continuum. I am working quantitatively on this correlation at the present time. Perhaps a tentative picture that would fit the observations is that Seyfert 1 galaxies are objects in which the mass inflow in an accretion disk around a central black hole is not steady. Perhaps occasionally the luminosity becomes larger than the Eddington limit, and gas is then expelled from the central accretion disk. This would give rise to something like expansion, but in a more or less flat plane, which would then give orientation effects and a range in the observed emission-line widths. Certainly there is considerable structure in the observed line profiles. There must be structure both in space and in velocity, which can be described as turbulence or as cloud motions. Comparison of physical models with the observed line profiles, intensity ratios, and continuous spectra seems to be the way to make progress in understanding these objects.

Finally I would like to briefly describe some of my current work on the optical spectrum of Q2 208 = Mrk 668. Part of these results have recently been published (Osterbrock and Cohen, 1979), while others are new since then. Q2 208 is a radio source identified with a compact galaxy. Its optical spectrum shows broad H I lines and forbidden narrow lines. Its magnitude is \(B \approx 6\) but varies with a range.
of about 1 magnitude. The radio spectrum has recently been discussed in detail by Kojoian, Dickinson, Toimassian, and Dinger (1978). It peaks near 7.9 GHz and has a form that suggests a synchrotron source immersed in thermal ionized gas, as the effects of free-absorption can be seen at low frequency.

Our first optical spectra, taken in July 1978, show broad H I and narrow forbidden lines, in other words, a typical Seyfert 1 or broad-line radio-galaxy spectrum. The spectra show no sign of Fe II, and [O III] is strong with respect to Hβ, the spectrum of a typical broad-line radio galaxy. However OQ 208 is unique in the large redshift difference between the broad lines and narrow lines, the broad lines having the larger redshift. Furthermore the optical spectrum varied between July 1978 and March 1979. On the latter date it appears that both the continuum and the broad lines were fainter by about 0.2 magnitude, while the forbidden lines and narrow Hβ are unchanged and therefore more easily seen. The measured difference is Δz = z (broad) - z (narrow) = + 0.0094 = 2800 km s⁻¹. If the origin of the redshift of the broad H I emission lines in OQ 208 were gravitational, this difference in redshift together with an assumed R = 0.03 pc, a representative figure from the emission line models described, the mass required would be \( M = 6 \times 10^9 M_\odot \). A gravitational origin however seems unlikely, particularly since different H I lines have different line profiles, especially Hα. More likely OQ 208 is probably like the fairly large fraction of Seyfert 1 galaxies which have asymmetric broad H I line profiles. About one-third of the known Seyfert 1 galaxies share this property, all of them having a wing extending to long wavelengths with respect to the peak velocity, which is usually very close to the velocity of the narrow H I and forbidden lines. Among ten Seyfert 1 galaxies in our survey having the most asymmetric H I lines, Δz = 0.0040 to 0.0076, of the same order of magnitude as, but smaller than, the redshift difference in OQ 208.

The interpretation of these profiles suggested by Shields (1978), Capriotti, Foltz and Byard (1979), and by Ferland, Netzer and Shields (1979) is expansion of the dense gas away from the nucleus with dust or line self-absorption. In this situation the H I line photons escape preferentially from the ionized side of the cloud toward the source of ionization in the nucleus. We thus preferentially see dense gas on the other side of the nucleus going away from us, while the dense gas on our side of the nucleus coming towards us suffers greater absorption or extinction. Although the situation envisaged by these authors is spherically symmetric expansion, I believe that the same sort of profiles would occur for expansion in a plane as in the model described above.

I plan to continue this observational study, and calculation of the expansion in a plane and other physical models through the stage of predicting profiles is clearly important. We may finally hope from comparison of such models with observational data to eliminate all but one final correct physical interpretation of the mechanism of broad-line radio galaxies and Seyfert galaxies.

I am very grateful to all the faculty and staff members of Lick Observatory mentioned above for their many important contributions in developing this scanner as a highly productive research instrument. I am also most grateful to all the people who collaborated with me in various stages of the research program described, especially J.S. Miller, G.K. Miley, S.A. Grandi, J.M. Shuder, R. Costero, A.T. Koski, M.M. Phillips, J.E. Tohline, R.K. Wallace, S.A. Hawley, R. Cohen and B.F. Hatfield. Finally, I should like to express my gratitude for continuing support of this research by the National Science Foundation under Grant AST 76-18440.
QUOTED LITERATURE


DISCUSSION

Peimbert: Has there been any systematic search for variations of the broad emission lines?

Osterbrock: Not at Lick Observatory. It is a very important problem, I think. We have discovered a few variations, pretty much by accident, and I think there must be many more that are there. We are, at Lick, getting into operation relatively soon a 40-inch telescope which will have the original Wampler-Robinson scanner on it. And I hope that it will be at least partially assigned to programs of that kind.

Peimbert: What would be the typical time of variation for a broad spectral line?

Osterbrock: We don’t observe systematically enough to be sure; we typically observe an object and then, if we don’t get a really good spectrum, we observe it a year later, and the variations we have seen have been in times like a year. If you look at the light variations that have been reported for these galaxies they are all for Seyfert 1 or broad-line radio galaxies. There aren’t any variations reported for narrow line objects, and typically their time scales would be of the order of months, or years, but not days. But again you don’t know how systematically people have observed them.

M. Burbidge: What are the shortest time-scales you have observed? Are the variations cyclic?

Osterbrock: The shortest time-scale that we have observed is three months, in NGC 7603. We haven’t observed it systematically enough to know if it is a cyclic behavior or not. Looking at the optical variations that are recorded, it doesn’t seem to be cyclic.