OBSERVATIONS OF SEYFERT GALAXIES WITH THE INTERNATIONAL ULTRAVIOLET EXPLORER

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ABSTRACT

The most important observations of Seyfert nuclei to be done in the ultraviolet are 1) the determination of the non-stellar continuum energy distribution and 2) the measurements of the intensities of the permitted lines. The main results obtained so far with IUE on these two points are as follows.

The Lyman/Balmer intensity ratio is smaller than predicted by the recombination theory. It cannot be forced into agreement with recombination theory by applying the reddening correction relevant to the narrow line region nor to the continuum. This Lyman/Balmer ratio is therefore caused by the particular physical conditions prevailing in the broad-line region. The smallness of the Lyman/Balmer ratio and the non-detection of the resonance lines of FeII neither in emission nor in absorption show that collisional processes play a dominant role in the excitation of the lines in the broad-line region and that the density in this region is at least 3×10^{10} cm^{-3}.

The energy distribution of the non-stellar continuum has been determined in a few Seyfert nuclei; it shows a variety of spectral shapes indicating that either the various components which can contribute to the observed continuum radiation -- non-thermal radiation, thermal radiation at various temperatures -- have different spectra in different objects or have the same spectrum but different relative intensities in different objects. The reddening, as deduced from the absorption feature at λ2175 also shows a large range of values corresponding to $0 \leq E_{B-V} \leq 0.40$.

1. INTRODUCTION

The characteristic of Seyfert nuclei is to possess a source of continuum radiation of non-stellar origin, with a spectrum extending in the far ultraviolet and producing the highly ionized elements (HeII, NeV etc.) observed in the optical spectrum of these nuclei.

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This non-stellar continuum is directly observable from the ground in Seyfert nuclei of type 1. Intensity variations of the continuum on a time scale of a few days have been observed and imply that the size of the continuum source is at most 10^{16} cm.

In the spectra of type 1 Seyfert nuclei, the lines of H, He and FeII have very broad components with widths corresponding to at least 5000 km s^{-1}. The intensity of the broad lines is variable on a time scale of a few months and, therefore, the dimension of the broad-line region is a few 10^{17} cm. The absence of broad forbidden lines in Seyfert nuclei implies that the particle density in the broad-line region is at least 10^8 cm^{-3}.

A third region can be identified in Seyfert nuclei: it is the region producing the numerous forbidden lines and the narrow components of the permitted lines. This region is spatially resolved in the nearby Seyfert galaxies NGC 1068 and NGC 4151; its dimension is therefore of the order of 100 pc.

It is clear that the most important problem relative to Seyfert galaxies is to identify the nature of the central energy source. The observation which is particularly crucial to make some advance on this problem is to obtain the spectrum of the continuum non-stellar radiation. Also, since broad lines are observed in galaxy nuclei only when a non-stellar continuum source is also present, the broad-line region is closely related to the energy source and its study is therefore relevant to this problem.

Ground-based observations do not permit to unambiguously determine the energy distribution of the non-stellar continuum for the following reasons. Firstly, at wavelengths larger than 2 μm, the infrared emission is due, at least in parts, to re-emission by dust of radiation originally produced in the ultraviolet. Secondly, in the range 0.35 μm to 2 μm there is the contribution of the stellar light. Thirdly, there is evidence in some objects, such as 3C 120 (Oke and Zimmerman, 1979), that the non-stellar emission changes slope near 4000 Å suggesting that there are at least two components to the non-stellar continuum radiation: a relatively steep, possibly non-thermal, continuum of the form $f_\nu \propto \nu^{-\alpha}$ with α in the range 1 to 0.5 and a flatter continuum which can be either a power law continuum with α near 0 or thermal radiation corresponding to a range of temperatures above 10^4 °K; evidently, observations in the ultraviolet are necessary to elucidate the nature of this flat-spectrum component. Fourthly, the observed energy distribution is affected by the absorbing material along the line of sight to the continuum source; the reddening correction to be applied to the continuum radiation is highly uncertain. It is hoped that, if it is correct to assume that the absorbing material along the line of sight to the continuum source, in particular in the Seyfert nucleus, has the same properties as in our galaxy, the observation of the absorption feature at λ2175 will give a direct measure of the reddening affecting the observed continuum radiation.

In addition to giving the spectrum of the non-stellar radiation, the ultraviolet observations provide the intensities of the Lα, CIVλ1550, CIII]λ1909 and FeII lines, all lines coming from the broad-line region; it is shown below how from the intensities of these lines it is possible to determine the density in the broad-line region.

2. RESULTS ON THE CONTINUOUS SPECTRUM

2.1. The energy distribution of the non-stellar continuum

The energy distribution of the non-stellar continuum radiation has been determined in a few Seyfert nuclei; it shows a variety of spectral shapes indicating that either the various components which can contribute to the observed continuum radiation (non-thermal radiation, thermal radiation at various temperatures etc.) have different spectra in different nuclei, or have the same spectrum but different relative intensities in different nuclei. Results on individual Seyfert nuclei are summarized below:

- In NGC 4151, the [SII] line intensity ratio, I(4032)/I(10320), gives E_{B-V} = 0.24 whereas the depression observed at λ2175 gives E_{B-V} = 0.1. The latter value represents a modest amount of reddening. The observed continuum radiation can be rather well fitted by $f_\nu \propto \nu^{-0.8}$ which becomes $\nu^{-0.7}$ after correction for the reddening corresponding to the absorption feature at λ2175 (Perola et al., 1979).
- In Markarian 79, the absorption near 2175 Å gives E_{B-V}= 0.22. The optical and ultraviolet continuous spectrum before correction is approximately fitted by $f_\nu \propto \nu^{-1.0}$ and becomes $\nu^{-0.5}$ after correction for reddening. The signal-to-noise ratio of the observed spectrum near 2200 Å is not sufficient to determine whether the absorption feature is at rest wavelength or redshifted (Oke and Zimmerman, 1979).
- In 3C 120, the λ2175 absorption feature is very deep and approximately corresponds to E_{B-V} = 0.38 (Oke and Zimmerman, 1979).
- Preliminary results relative to NGC 1068, one of the very few Seyfert 2 galaxies which has been observed with IUE, can be summarized as follows (J.B. Oke, private communication): the relative intensities of the hydrogen lines of the Lyman, Balmer, Brackett and Paschen series, as well as the ratio of the HeII lines I(1640)/I(4686), all agree with recombination theory after a reddening correction of E_{B-V} = 0.4 has been applied. The ultraviolet continuum shows no absorption at λ2175 and its spectral shape with no reddening correction applied is consistent with $f_\nu \propto \nu^{-\alpha}$, with α very close to 0.

Finally, it must be kept in mind that some of the most informative Seyfert nuclei show intensity variations. A meaningful interpretation of their optical and ultraviolet spectra in terms of various components requires that both spectra be observed essentially at the same time.

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2.2. Absorption lines

Two types of absorption lines are expected to be present in the ultraviolet spectrum of extragalactic objects. The first type of lines are the lines caused by the absorbing material in the halo of our galaxy. These lines (CII, SiII, CIV etc., at zero redshift) have been detected in the IUE spectra of 3C 273 (Ulrich et al., 1979). Extragalactic objects offer the advantage that their spectra make it possible to study the absorbing material in the entire galactic halo whereas halo stars evidently give information on the inner part of the halo only. In fact, comparison of the strength of the CIVλ1550 absorption line in 3C 273 and in halo stars leads to the conclusion that most of the CIVλ1550 absorption along the line of sight to 3C 273 is caused by hot material located in the outer part of the halo. Similar results can in principle be obtained from other extragalactic objects provided the continuum is recorded with a good signal-to-noise ratio.

The second type of absorption lines which can appear in the spectrum of a Seyfert nucleus are the lines which are intrinsic to the nucleus itself. Such lines have been observed in the nucleus of NGC 4151 (Perola et al., 1979) and of NGC 3516 (Ulrich, in preparation). Both nuclei show eight absorption lines with equivalent widths of several angstroms and therefore too strong to be caused by the halo of our galaxy. NGC 4151 has been observed a dozen different times since IUE was launched and preliminary analysis of the spectra seems to indicate that the absorption lines vary in intensity; further study of these variations is in progress.

3. RESULTS ON THE BROAD-LINE REGION

3.1. The Lyman/Balmer intensity ratios

It has first been noted by Baldwin (1977) that in quasars, the intensity ratio Lα/Hβ is close to 5, whereas recombination theory predicts values in the range 22 to 40 depending on the amount of collisional excitation of Lα. In all the Seyfert 1 nuclei where this ratio has been measured, it has also been found in disagreement with the recombination theory. The results on individual objects summarized below show that this ratio cannot be forced into agreement with recombination theory by applying the reddening correction relevant to the continuous radiation nor to the narrow-line region.

In the case of Markarian 79 (Oke and Zimmerman, 1979) a reddening correction twice as large as the continuum reddening is required to yield agreement of the ratio Lα/Hβ with recombination theory. Similarly, in NGC 4151 (Perola et al., 1979) the reddening correction for the continuum, $E_{B-V} = 0.1$, gives Lα/Hβ = 7 and is therefore insufficient to yield agreement of the ratio Lα/Hβ with recombination theory. On the other hand, in 3C 120 the continuum reddening is very large and assuming that it applies also to the broad permitted line, the ratio Lα/Hβ becomes approximately that predicted by recombination theory (Oke and Zimmerman, 1979).

It has long been suspected that the reddening estimated from line intensity ratios in the narrow-line region is not relevant to the broad-line region. This has been confirmed by the ultraviolet observation of 3C 390.3 (Ferland et al., 1979). In this object, the broad component of the permitted lines can be easily separated from the narrow component. It has therefore been possible to measure the ratio Lα/Hα separately for the narrow components and for the broad components. It is found that, for the narrow components, this ratio is in agreement with recombination theory but that for the broad components the value of the Lα/Hα ratio is close to that found in quasars or the other Seyfert nuclei mentioned earlier. This result clearly illustrates that the broad-line region has a peculiar Lα/Hα ratio whatever is the reddening correction relevant to the narrow-line region. It can therefore be concluded that the small Lα/Hβ ratio in quasars and Seyfert nuclei is caused by the physical conditions in the broad-line region. Since the particle density in the broad-line region is very high, collisional processes are likely to play an important role in the excitation of the lines.

This question has recently been investigated by a number of authors (Baldwin, 1977; Netzer and Davidson, 1979; Ferland et al., 1979). It seems that the small Lα/Hβ ratio is not primarily caused by a decrease of Lα because the equivalent width of Lα in high redshift quasars is consistent with the number of ionizing photons in the extrapolated continuum (Baldwin, 1977); a similar result is obtained in the case of 3C 390.3 by Ferland et al. (1979). The small ratio Lyman/Balmer can be produced by an enhancement of the Balmer lines: since the optical depth in Lα is large, the first excited state is significantly populated and Balmer lines are collisionally excited out of the first excited state (Ferland et al., 1979).

3.2. The FeII lines

A number of FeII lines, all broad and permitted, and in the wavelength range 4500 to 6500 Å, are present in the spectrum of several Seyfert nuclei and quasars. For the purpose of discussing the excitation of these lines, the FeII ion can be considered as a 3-level ion with a level at 3 ev, a level at 5 ev and the ground state. The lines observed in the optical range correspond to the transition from the 5 ev to the 3 ev level. The transitions from the 3 ev level to the ground are forbidden and are not observed.

Two mechanisms can populate the upper level: firstly as proposed by Wampler and Oke (1967), the 5 ev level could be populated by fluorescence; in this case, one expects to observe absorption lines in the ultraviolet continuum at the wavelength of the resonance lines, ground state to 5 ev level, i.e. in the range 2300-2900 Å. The second mechanism for populating the 5 ev level is collisions; in this case the resonance lines in the ultraviolet should appear in emission.

The IUE observations of several Seyfert nuclei which have prominent FeII lines in their optical spectrum show no absorption at the wavelengths of the resonance lines [3C 390.3 (J.B. Oke, private communication); IZWI, IIZw 136, MK 231 (A. Boksenberg, private communication)]. Similarly no QSO with FeII line in the optical range, shows FeII absorption lines in the ultraviolet. From these results, it is concluded that the optical lines of FeII are not excited by fluorescence.

On the other hand, no resonance lines have been detected in emission either. Recent calculations have shown that this is compatible with collisional excitation of the optical lines (Jordan, 1979; Collin-Souffrin et al., 1979) if the density in the broad-line region is $\sim 3 \times 10^{10}$ cm^{-3}; with such a high density, the resonance lines are destroyed by repeated resonant absorptions and become undetectable. Note, however, that the detection limit of IUE for emission lines is large, being 10 to 20 Å in equivalent width.

The fact that the semi forbidden line CIII]λ1909 is broad and rather intense in Seyfert nuclei and in quasars, is often used to set an upper limit of about 10^9 cm^{-3} to the density of the broad-line region. However, recent calculations by Nussbaumer and Schild (1979) show that in at least one quasar where both lines of CIII, λ977 and λ1909, have been measured, and where λ1909 has a typical intensity, the intensity ratio I(977)/I(1909) is compatible with a density of 3×10^{10} cm^{-3} for a temperature of 15000 °K. The CIII]λ1909 line can therefore be emitted in a region with a density of 3×10^{10} cm^{-3}.

3.3. Conclusions

The observations with IUE of the Lα/Hβ ratio and the non-detection of the FeII resonance lines, together with recent theoretical calculations of the hydrogen line ratios and of the FeII line intensities, all converge to indicate that collisional processes rather than photoionization play the major role in the excitation of the lines in the broad-line region and that the particle density in this region is of the order of 3×10^{10} cm^{-3}.

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DISCUSSION:

M. Penston: I would like to clarify Marie-Helene's remarks concerning the Fe II emission. This is indeed seen in the U.V. spectra of II Zw 136, Mk 231, and NGC 1566: the lines that are seen are those of U.V. multiplets 63 and 64 just shortward of 2800 Å. The resonance lines are not, to my knowledge, seen in any object. The other interesting thing is the weakness of the U.V. lines (even those descending to lowly excited states) relative to the values expected from the intensities of the optical lines and the branching ratios. This is particularly interesting as it shows that low-lying states of Fe^{+} are populated and gives some hope of determining the temperature.

M. - H. Ulrich: Yes, I agree with Michael Penston that the detection of these weak U.V. lines of Fe II multiplets 63 and 64 is very interesting since these lines can give some information on the temperature.