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ACTIVE GALAXIES OBSERVED BY IUE

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ABSTRACT

IUE has extended the grasp of ultraviolet astronomy to cover active galaxies and quasars fainter than the sixteenth magnitude. These observations have:

(i) provided a diagnostic for the source of ionization in active galaxies,
(ii) cast light on the excitation mechanism of the Fe II lines,
(iii) shown the broad hydrogen lines in Seyferts and quasars are not in their recombination ratios,
(iv) demonstrated the absence of gas in BL Lac objects,
(v) supported the gravitational lens explanation of the double quasar,
(vi) demonstrated the presence of a hot (30 000 K) black body in active nuclei,
(vii) discovered stratification of the ionization conditions in the Broad Line Regions of active nuclei.

1. ULTRAVIOLET CONTINUUM OF SEYFERT 2 GALAXIES

The first topic to be discussed in this article connects up to the preceding review of Normal Galaxies by Gondhalekar [1] since it also concerns the ultraviolet rising branch in the spectra of active galaxies. In the two cases of NGC 1052 and Pks 2158-380, for example, the overall forms of the ultraviolet continuum spectra are similar yet we believe the source of the ultraviolet component is hot stars in NGC 1052 whereas it appears to be a non-thermal power law in Pks 2158-380. The main reasons for believing this are based on the character of the optical and ultraviolet emission line spectra.

Low resolution observations of the active elliptical galaxy NGC 1052 have been obtained by Fosbury et al. [2] in both long and short wavelength regions. When combined with optical multiaperture photometry, these demonstrate a low reddening E(B-V) ~ 0.06. In spite of the presence of the radio source, there is no evidence for a compact source of non-thermal radiation capable of ionizing sufficient gas to emit the observed Balmer line flux. The strongest ultraviolet emission lines are CII] λ2326 and CIII] λ1909, a situation similar to that in the Cygnus loop supernova remnant suggesting shocks as the ionization mechanism in this galaxy.

Pks 2158-380 is another radio-emitting elliptical studied by Fosbury et al. [3] but has a much higher excitation emission line spectrum. In this case the ultraviolet energy distribution, which is consistent with a power law $f_\nu \propto \nu^{-1.3}$ shortward of 2800 Å, probably is the source of ionization. Emission from Lα, C IV and He II is detected, also consistent with photoionization. The hydrogen and helium lines are in their recombination ratios and have strengths expected from an extrapolation of the power law to 228 Å. The IUE data, together with that from other wavebands, suggest an interpretation of the emission lines in terms of a warped disc of excited gas, lying in the elliptical galaxy and illuminated by the active nucleus.

Other Seyfert galaxies of type 2 for which IUE observations have been reported in the literature include NGC 1068 [4, 5], NGC 7582 [6], NGC 4057 and 5506 [7]. In all these cases the ultraviolet continuum appears to be dominated by a non-thermal power law which represents the main source of excitation and ionization. The existence of this power law had long been suspected from observations of the optical continuum and believed to be necessary to account for the high excitation emission lines but is now unambiguously demonstrated by IUE. It provides a tangible link between the Seyfert galaxies of types 1 and 2 by indicating the existence of relativistic particles in both classes of object.

2. REDDENING AND THE Fe II EMISSION SPECTRUM

One parameter which is obviously important for determining the true continuum shape is the intrinsic reddening. It is convenient and has become traditional to determine this by applying a galactic reddening law (usually that of Seaton [8] to remove any absorption feature that may be present at λ2175. Examples of this approach may be found in the above cited papers on Seyfert 2 galaxies [6, 7] but it has also been applied to Seyfert 1 galaxies [9, 10, 11], BL Lac objects [12, 13] and even quasars [14].

It cannot be denied that there are considerable hazards attached to any overconfident reliance on an estimate of the reddening derived in this way. First of all, as is reported elsewhere [15, 16], it is now clear that the LMC reddening curve is quite different from the galactic one with a much weaker λ2175 dust signature. Second it is also apparent that the same reddening may not apply to all components of a single source (e.g. continuum, broad lines, narrow lines etc.). In addition a further hazard, which I wish to stress, is the "fake" λ2175 which appears to be present in objects with strong Fe II emission.

Before briefly discussing the Fe II problem, it is perhaps worth recalling the understanding of the Fe II line formation current at the time of the launch of IUE. Two theories existed which gave diametrically opposed predictions for the ultraviolet FeII lines. It was held either that the optical FeII lines were excited by collisions or by resonance fluorescence with predictions of powerful ultraviolet emission (from the branching ratios) or strong absorption (to power the optical lines) respectively. In 1978 February, we therefore waited expectantly for the first IUE spectrum of 3C273 confident this problem would soon be cleared up! In the event as we now know the lines are in emission but much weaker than suggested by these initial predictions and the first report [4] was that the lines were absent in either emission or absorption. I must say that, in the event, the theoreticians were not perplexed for long and soon found an explanation in terms of collisional excitation with radiative transfer in the ultraviolet resonance lines trapping the photons until they leak out in the optical [17, 18, 19].

Observational developments have since gone in parallel in the optical and in the ultraviolet. Various composite spectra have been constructed from ground based data [20] showing a characteristic set of emission blends generally accepted to be Fe II. At the same time Snijders et al. [21] made low dispersion IUE observations of the Seyfert 1 galaxies I Zw I, II Zw 136 and Mk 231, which all have very strong Fe II emission lines in the optical region. The ultraviolet spectra of I Zw 1 and II Zw 136 are very similar: both are variable and show the broad emission features of Fe II (especially the UV multiplets 1, 33, 60, 62 and 63) as well as other emission lines usually strong in Seyferts and quasars, e.g.: Lα, Mg II, C III], C IV and N V. Mk 231 however has a completely different ultraviolet spectrum: there is no evidence for variability and only low ionization lines of Mg II, Fe II and Lα are present (both in emission and absorption); the strongest absorption lines all belong to the z=0.043 system, which is probably of stellar origin.

One characteristic of the Fe II emission blends, visible in figures in the references cited above, is a gap between emissions close to λ2175 which leads to the "fake" dust absorption mentioned earlier. It is a very credible alternative to the intrinsic dust absorption in 3C273 claimed by Ulrich et al. [14] and, I personally now believe, a more plausible one. It leads of course to the need to reassess the inter pretation of the continuum spectrum and the values of the line intensities given in that paper. This method of measurement of reddening in quasars and Seyfert type 1 galaxies generally must be suspect since they are likely to have Fe II emission. We shall return to this question again in Section 6.

3. OTHER RESULTS FROM EMISSION LINES

Apart from its contribution to the Fe II problem, another important area also involving the broad emission lines from active objects to which IUE has been well suited has been the famous Lα/Hβ problem. Originally found from composite ground based spectra of quasars at different redshifts by Baldwin [22], this is posed by a much lower observed Lα/Hβ ratio ($\sim$ 6) from that predicted theoretically from Case B recombination (20–40). In fact IUE data have greatly strengthened this conclusion by demonstrating this effet in many individual objects in which Lα intensities observed by IUE can be compared with Balmer line intensities from ground data. These have included results on 3C273 [4, 14, 23], NGC 4151 [4], PG 0026+129 [24] 3C390.3 [25, 26, 27] Ak 120 [28] and studies of several objects [9, 29, 30].

The theoretical implications of the discrepant Lα/Hβ ratio have been discussed elsewhere and the interested reader is referred, for example, to the review by Davidsen [31]. Explanations include internal or external red dening, collisional excitation from the first excited level and line transfer effects. It is however worth noting here one or two observational points.

In particular, in low luminosity objects it is necessary to separate broad and narrow line components because their line ratios may well be different. A particularly interesting case is 3C390.3 first studied by Ferland et al. [25] who made separate determinations of the Lyman/Balmer ratios in both the narrow and broad emission-line regions. The broad-line Lα/Hα ratio confirmed the anomalous results first found in quasars - in this case a ratio was found about 15 times smaller than that predicted by simple recombination models. By contrast, the Lα/Hα ratio found for the lower density narrow-line region was found to be nearly normal. Since then the same galaxy has been studied by Barr et al. [26] who pointed out difficulties with the divergence of different reddening estimates and that the narrow line ratios were also different from Case B predictions. Most recently Netzer [27] discussed the object again and concluded that there are theoretical reasons why even the narrow line ratios (neither Lα/Hβ nor Hα/Hβ) may not fit Case B for low-density gas near a strong non-thermal source.

A further interesting wrinkle in the story is the recent report of a Lα/Hβ ratio close to the Case B value in 3C351 [32]. Whether this result has any intrinsic significance or is a fluke is as yet unclear.

The C IV λ1550 line intensities have also been measured in many objects by IUE and provide a chance to check whether the cosmologically-important Baldwin [33] relationship between quasar CIV equivalent widths and continuum luminosities also applies to a very different sample of active objects. While it seems that "quasars" comply well with the Baldwin relationship [34] data on Seyfert galaxies [35] by contrast shows that they deviate. In addition one notes that BL Lac objects must also violate the relation. Thus it is a correlation fitted only by a subset of all active objects which might have been supposed to have a continuum of physical properties. My strong impression is that there is some feature of the definition of "quasars" which implies they fit the relationship - in other words observational selection effects are playing a hand.

Line profiles in active galaxies are discussed in several papers, in particular high dispersion results on NGC 4151 by Penston et al. [36] and for a wide sample of objects by Wu et al. [37].

4. BL LAC OBJECTS

Early in its life, IUE contributed to establishing that the lack of emission lines in BL Lac objects is due to absence of gas and not, as had originally appeared possible, an absence of ionizing photons. Ultraviolet observations of the BL Lac objects Mk 421 and Mk 501 showed continua running to the short wavelength cut-off of IUE without any emission lines. These continua provide enough photons to ionize any gas present in these galaxies and this should result in easily detectable but unobserved Lα and Hβ. However when I announced this result at the Pittsburgh meeting on BL Lac Objects [38], I was questioned by Krolik whether IUE observed O VI λ1032. Apparently he had a model in which the gas was so hot that only this line would be seen! At the time I had no answer but now there are observations of BL Lac objects of high enough redshift that this can also be excluded. There is still an escape clause however as any gas might be concentrated so that it only subtended a very small solid angle at the ionizing source. One can only conclude that there is no gas in these objects in the same geometrical state found in Seyferts and quasars.

Other results on BL Lac objects observed by IUE are reported by Maraschi et al. [39], Bromage et al [40], Kondo et al. [13], Fricke et al. [41] and Bregman et al. [42]. The results on continuum shapes are beginning to show some systematics which are discussed by the last named authors.

5. THE DOUBLE QUASAR

Another of the great triumphs of IUE was the contribution made by Gondhalekar and Wilson [43] to the story of the double quasar 0957+561 AB. These authors showed that the intensity ratio A/B in the ultraviolet was the same as in the radio. In the optical the ratio is different and varies with wavelength. Originally there were suggestions that this was due to different reddening values on the different paths to A and B [44] but now this is recognized as due to contamination of component B by the lens galaxy. Gondhalekar and Wilson found identical spectra with a ratio B to A, constant with frequency, of 0.72 ± 0.05 because the ultraviolet spectra are essentially uncontaminated. These results and the agreement of the ultraviolet and radio values of this ratio provided strong evidence for the gravitational lens hypothesis.

More recently the same authors have reported on ultraviolet variations of the double quasar [45]. They find that the A/B ratio varies in the same way as the optical but that it seems component A is variable in the ultraviolet contrary to the constancy of A and variability of B in the optical [46, 47]. This mysterious result is currently unexplained as either instrumental or astrophysical effects.

6. VARIATIONS IN SEYFERT 1 GALAXIES

Thus far in this review article, the skeleton of the results reported have been apparent to those in the field for some time and the bulk of the work in the last 18 months has consisted of putting flesh on these bare bones to support and clarify the established picture. In my view, the most spectacular recent jump in our knowledge in the active galaxy field to flow from the IUE data is that derived from the various studies of variability of Seyferts of type 1. A particularly favourable case for study is the bright northern Seyfert NGC 4151 which has been the target of the so-called "European Extragalactic Collaboration" (EEC) of astronomers throughout Europe.

Originally [11] from data at the first six epochs, they showed there are eight different variable components measured by IUE:

(i) the fine-error sensor (optical) magnitude

(ii) the long wavelength continuum

(iii) the short-wavelength excess over the extrapolation of (ii)

(iv) the short wavelength emission lines

(v) the high excitation equivalent widths (N V, C IV, Si IV) of absorption lines

(vi) the low excitation equivalent widths (Al III, Si II*) of absorption lines

(vii) the width of the C IV emission line and

(viii) the ratio of red-to-violet peaks in C IV.

Now however from data at 31 epochs, the systematics are becoming clearer [48, 49, 50]. The continuum is described by 3 parameters, the slope and intensity of a power law that fits well in the region 2000 - 3000 Å and an excess seen at shorter wavelengths, 1000 - 2000 Å. The power law component steepens as it fades. The short wavelength excess is however not simply correlated with the power law component. It is generally constant but becomes fainter at a few "anomalous" epochs.

The high ionization absorption lines as well, are found to be correlated with the power-law component and it is therefore deduced that this is the dominant source of ionization near 300 Å.

This implies that the "short wavelength excess" must turn down exponentially between 1000 and 300 Å in a way similar to that of a thermal source with T ~ 30 000K. Thus the short wavelength excess may represent thermal radiation from an accretion disk as originally proposed by Shields [51]. The low ionization absorption lines, by contrast, are anti-correlated with the continuum.

The strong emission lines each show different widths, in contrast to the common situation in quasars, except at anomalous epochs when all emission lines are relatively narrow (8000 km s^{-1}). The CIV intensities are well correlated with the continuum but there is some hysteresis associated with a lag of 15-20 days. This delay is caused by light travel times in the CIV emitting region. The Mg II emission region seems to be bigger, perhaps 80 light days in diameter - so that the continuum variations are somewhat smeared out - whereas the lack of variation in C III] suggests an emission region larger than a light year.

From the three strong lines giving both a velocity from their width and a size from their variability properties, one can deduce v^2r which is proportional to a mass. These three independent estimates converge on a value of 10^8 $M_\odot$. This is particularly interesting as the area of an accretion disk capable of thermally emitting the flux in the short wavelength component suggests a linear dimension about one order of magnitude greater than the Schwarzschild radius for this mass, in other words comparable to the radius of the last stable orbit [52] around a gravitating object.

Another interesting result from the correlation diagram of the C IV intensity against the long wavelength continuum [49] is the fact that the anomalous epochs appear at times (according to the hysteresis interpretation) when the long wavelength continuum is fading. In other words the power-law fades when the disk, which provides the fuel supply, is off or weak. Thus the variability data allow one to deduce a chain of cause-and-effect: events are first seen in the thermal (disk) component, later in the long wavelength (power-law) component and last in the emission lines.

A final result from NGC 4151 is the possibilities of kinematic and geometrical mapping of the broad line region by studying the development of the line profile in response to a sudden increase (or decrease) in the illuminating power-law source. One can, in principle, distinguish chaotic, rotary and radial motions in the emission region. Results to date for the C IV region suggest the dominant motion is chaotic although there may be a small radially outflowing component.

It is important, of course, to show that this intriguingly complex behaviour is telling us something about active objects in general and is not simply idiosyncratic to NGC 4151. Various other results have been reported for the variations of other Seyfert type 1 systems: e.g. Ak 120 [28, 53, 54], NGC 4593 [55], NGC 3783 [56], NGC 5548 [57] and a comprehensive study of several objects by Boisson and Ulrich [58]. The overall result seems to be that indeed the variations of the other galaxies are basically similar to those of NGC 4151 and that results for that particular system have a wider application to Seyfert galaxies in general.

A major problem however is raised by Barr et al. [56] who assert that the reddening is variable in NGC 3783. In this galaxy there must in addition be intrinsic variations in the underlying source but for NGC 4151 the referee of Perola et al. [48] also noted that whole variation of the power law component may be consistent with a variable reddening screen: this would make the continuum steepen as it faded. My belief is that this is unlikely to be the correct interpretation as in NGC 4151 it would require the screen to lie between the continuum source and broad line region in an environment extremely hostile to dust. Possibly the variations in reddening proposed by Barr et al. [56] can be attributed to variations in Fe II emission and the fake λ2175 effect discussed in Section 2. Nonetheless it is clear that further clarifying work is necessary on this point.

7. THE CONTINUUM OF QUASARS

Another important work on the existence of blackbody components in active nuclei is that by Malkan and Sargent [59] which combines the IUE data with optical scans. In the objects they study, including 3C273, the thermal component is much stronger and may be visible in the optical data alone. They find in several different objects, it always has a temperature in the range 20 000 - 30 000K.

Such black-body components should also be seen in the study of higher redshift objects. Such quasar data are reported by Wilson et al. [60] and Green et al. [29]. Wilson et al. [60] reported the detection of a rather faint quasar Q2204 ($m_U \sim 17.5$) down to a emitted wavelength of ~ 300 Å. They found a power-law continuum consistent with that usually seen at longer wavelengths. Possible He II λ304 was also reported. Green et al. [29] give several cases, some of which show a substantial turn down in the range 900 - 450 Å also consistent in a general way, at least, with the presence of a black body in the temperature range found above.

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