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IONIZING CONTINUUM AND EMISSION-LINE ENERGETICS OF QUASARS AND SEYFERT GALAXIES

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RESUMEN

Existe un renovado interés por las discrepancias en los contenidos energéticos del continuo ionizante, en combinación con ciertas mediciones de líneas de emisión anchas, para núcleos de galaxias activas. En este trabajo revisamos la historia de este dilema, y reexaminamos la situación a la luz de las observacionaes mas recientes y los avances en nuestro entendimiento de varios factores contribuyentes. El problema no es tan serio como se creyó, aunque aun existen algunas indicaciones de que el continuo observado, extrapolado al lejano UV, es energéticamente insuficiente para dar lugar a la fotoionización necesaria para explicar todas las líneas de emisión anchas que se observan en cuasares y galaxias Seyfert. Finalmente, se consideran varias posibles ramificaciones y resoluciones de las inconsistencias restantes.

ABSTRACT

There has been renewed interest in apparently discrepant energy budgets suggested by consideration of the observed ionizing continua in combination with certain broad emission-line measurements for active galactic nuclei. This discussion reviews the history for the worrisome dilemma, and the evolving situation is reexamined in light of the most recent observations along with improvements in our understanding of various contributing factors. The problem is not as serious as was once believed, although there are still some indications that *observed* continua, extrapolated to far ultraviolet wavelengths, are energetically insufficient to cause photoionization as necessary to account for all of the broad emission lines seen in the spectra of quasars and Seyfert galaxies. Several potential ramifications or resolutions of remaining inconsistencies are considered here.

Key Words: **GALAXIES: SEYFERT — QUASARS: EMISSION LINES — QUASARS: GENERAL — ULTRAVIOLET: GALAXIES**

1. EARLY HISTORY OF THE ENERGY BUDGET PROBLEM

Investigations which attempt to account for the broad emission lines in spectra of quasars and Seyfert galaxies, and thereby to derive valuable information about the primary energy source as well as the physical and chemical properties of the line-emitting gas, have generally assumed *apriori* that the gas is photoionized by a local, primary source of ultraviolet radiation. The line-emitting gas, in effect, "recycles" the primary ionizing continuum radiation, so there is an "energy budget" that must be considered. The gas should not produce more energy in the lines than that which is supplied by the primary source.

Early photoionization model calculations (e.g., Davidson 1972, MacAlpine 1972, Shields 1972) could incorporate primary ionizing continua which were *devised* to accommodate the energy budgets of the emission lines. Observational constraints for the ultraviolet continua were lacking, so one had the option of simply choosing an appropriate power-law or exponential extrapolation into the ultraviolet in order to provide the required energy.

In the early 1980s, as near-ultraviolet observations became available from the *International Ultraviolet Explorer (IUE)* satellite and as more high-redshift quasars were being discovered and observed from the ground, it became apparent that there might be a large energy-budget discrepancy in the sense that the line emission contained significantly more power than the available ultraviolet continuum radiation. The *IUE* data published by Green et al. (1980) (cf., Bechtold et al. 1984) suggested that the continuum radiation produced by quasars and Seyfert galaxies has a strong spectral downturn in the ultraviolet, for which the mean measured power-law spectral index shortward in wavelength from the rest-frame hydrogen $Ly\alpha$ line is $\gamma \approx -2.3$ (for ionizing luminosity $L_\nu \propto \nu^\gamma$, with L_ν in $ergs\ s^{-1}\ Hz^{-1}$ and ν being frequency). This was cause for serious concern when considered along with ground-based measurements for more than 50 high-redshift quasars, none of which showed a discernable spectral discontinuity at the Lyman edge (e.g., Smith et al. 1981, MacAlpine and Feldman 1982). The lack of absorption at rest-frame 912 Å for that many quasars implies that the continuous radiation is not intercepted by optically-thick gas over more than 90% of the 4π steradians of solid angle, Ω, around the ionizing radiation source. Therefore, for the so-called "covering factor," $\Omega/4\pi < 0.1$, and a maximum of 10% of the radiation from the primary source should be considered when computing the energy budget available to be recycled by the line-emitting gas.

MacAlpine (1981) and MacAlpine et al. (1985) demonstrated that the He IIλ4686 and He IIλ1640 emission lines of quasars and active galaxies can be expected to arise primarily from well-understood recombination processes and that measured, rest-frame equivalent widths for these lines may be used analytically to investigate the primary ionizing radiation spectral characteristics at unobserved far-ultraviolet wavelengths. Photons with $\lambda < 228$ $\mathring{A}$, which are absorbed by the line-emitting gas through photoionization of He^+, lead predictably to the production of the above recombination lines; and the line equivalent widths provide information about the ratio of the far-ultraviolet radiation to that at visible or near-ultraviolet wavelengths. The method involved is similar to the technique employed by Zanstra (1931) for characterizing radiation in planetary nebulae using H I lines (which may have significant collisional contributions in active galaxy spectra). The relevant mathematical expression for a line equivalent width is straightforward to derive (MacAlpine 1981). Using He IIλ1640 as an example, the energy production rate ($ergs\ s^{-1}$) in this recombination line may be written as

$$E(\lambda 1640) = N(He^{+2})\, N_e\, \alpha(\lambda 1640)\, h\nu\, V, \quad (1)$$

where the right side is the total photon production rate times the energy per photon, with N_e as electron density, $\alpha(\lambda 1640)$ being the effective recombination rate coefficient for the line, and V as the gas volume. For gas in ionization equilibrium,

$$\int_{4Ry} (L_\nu/h\nu) d\nu = N(He^{+2})\, N_e\, \alpha(He^{+2})\, V, \quad (2)$$

for which the left side is the total input rate of ionizing photons absorbed by He^+ (above the $4Ry$ ionization potential), and the right side is the total He^{+2} to He^+ recombination rate, with $\alpha(He^{+2})$ being the relevant recombination rate coefficient. For the emission line equivalent width (in $\mathring{A}$), we can write

$$EW(\lambda 1640) = 10^8\, (\lambda^2/c)\, [E(\lambda 1640)/L_\nu(\lambda 1640)], \quad (3)$$

where $L_\nu(\lambda 1640)$ is the continuum value at the position of the line. Combining equations (1), (2), and (3), we have a useful analytic expression for the line equivalent width in terms of atomic and spectral parameters,

$$EW(\lambda 1640) < 1640\, [\alpha(\lambda 1640)/\alpha(He^{+2})] \times [\int_{4Ry} (L_\nu/\nu) d\nu / L_\nu(\lambda 1640)]\, \Omega/4\pi, \quad (4)$$

in which the inequality results from multiplication by the assumed covering factor which is an upper limit. By considering the best available measurements for the relevant line equivalent widths (e.g., Osterbrock 1977, Uomoto 1984), along with the best available optical–ultraviolet–X-ray continuum spectra, energy budget discrepancies of nearly a factor of 100 were deduced for both lines! Therefore, it was suggested that the intrinsic ionizing radiation seen by the line-emitting clouds may be much more energetic than implied by the reported ultraviolet IUE continuum measurements.

Furthermore, it was soon also recognized that the total rate of ionizing radiation energy input to the broad-line gas appeared to be much less than the power emergent in the emission lines. Eastman et al. (1983) noted that some measurements yielded roughly the same amount of energy in the extrapolated ionizing continuum (even without taking into account the low covering factor) as in the $Ly\alpha$ line alone. They suggested the possibility of more energetic (than observed) intrinsic ionizing spectra, for which a steep, soft X-ray spectrum reported by Pravdo et al. (1981) might be a high-energy exponential fall-off, characteristic of emission from very hot gas.

Netzer (1985) joined the line energy controversy by pointing out that contributions from many other lines may account for 3–8 times (depending on reddening) more energy than $Ly\alpha$, further compounding the problem. Therefore, the energy budget discrepancy between measured line fluxes and observed power in the ionizing continuum appeared to be almost as extreme as that suggested by measured He II line equivalent widths.

2. A PARTIAL RESOLUTION

The discrepancy between quasar ultraviolet continua and the requirements to produce measured He IIλ1640 line equivalent widths received renewed attention when it was again reported by Korista et al. (1997). However, the most interesting aspect of that new announcement is the fact that the reported discrepancy had diminished.

For the ionizing radiation input to numerical photoionization models, Korista et al. used a composite quasar spectrum published by Zheng et al. (1997), which contains *Hubble Space Telescope (HST)* data for 101 quasars and extends to roughly 305 Å in the source rest frame. Korista et al. compared calculated results from their models with the composite He IIλ1640 rest-frame equivalent width measurement from Zheng et al. (taking into account a gas covering factor less than 0.1) and concluded that the observed composite ionizing spectrum was "at least 5 times too weak" compared with the radiation field which must have been seen by the line-emitting gas.

Why did Korista et al. find a minimum discrepancy of only a factor of 5, as compared with a factor of nearly 100 as reported by MacAlpine (1981) and MacAlpine et al. (1985)? The representative, measured He IIλ1640 line equivalent widths considered in the different cases did not change that much, being about 4.5 Å (Zheng et al. 1997) and 6.8 Å (Uomoto 1984). The significant new information involves the difference between ionizing spectral power-law slopes considered. Whereas the *IUE* data suggested $L_\nu \propto \nu^{-2.3}$, the reported *HST* composite spectrum falls off as a -1.96 power law into the ultraviolet.

For this new spectral shape, the analytical expression for equivalent width in equation (4) yields $EW(\lambda 1640) < 1$ $\AA$. Compared with the newly reported $EW(\lambda 1640)$ measurement of 4.5 Å, the lower limit to the discrepancy had indeed changed to roughly a factor of 5; and it is clear that the new ultraviolet continuum data are responsible for considerably alleviating the energy budget problem. But, why have the reported continuum data changed? The answer probably involves corrections made by Zheng et al. to compensate for Galactic extinction and also for differential absorption due to intervening gas, both of which were carefully considered in their improved reduction processes.

3. FURTHER DIMINISHING THE PROBLEM

It has become evident that previously reported He II line equivalent width measurements have been too high for the most part, because the emission may be heavily contaminated and "enhanced" by prevalent Fe II features or multiplets. Using high signal-to-noise, high-redshift quasar spectra previously published by Weymann et al. (1991) and Junkkarinen et al. (1983), Lemanski and MacAlpine (1999) investigated complex emission features in the 1600–2250 Å range, giving very careful consideration to problems that may be encountered in the measurement of He IIλ1640. A common feature noted in the spectra is a "plateau" extending from roughly 1600 Å to 1680 Å, which involves emission from Fe II multiplets uv 8, 40, 42 and 43, as well as He IIλ1640 and O III]λ1663. In many cases, the Fe II emission appears to dominate, whereas one might mistakenly measure the entire plateau as He IIλ1640. For those quasars in which Lemanski and MacAlpine found Fe II emission to be relatively weak, so that He II and O III emission appeared better defined, it was judged that the He IIλ1640 measurements could still be inaccurate by a factor of 2 or more, depending on what one assumes for underlying Fe II uv 8, 42, and 43. Overall, the estimated He IIλ1640 rest-frame equivalent widths ranged from about 0.5 Å to 5 Å. Therefore, it has become apparent that some prior reported measurements of He II lines are probably too high and also that composite spectra may not be meaningful in this regard, since the lines may vary significantly from object to object.

Another issue worth considering is that the Zheng et al. (1997) quasar continuum discussed above did not involve very many sources extending to its short wavelength end near rest-frame 350 Å. In an effort to improve upon this situation, Telfer et al. (2002) used a sample of 332 *HST* spectra for 184 quasars, giving much improved ultraviolet spectral coverage; and they measured a revised spectral slope between 500 Å and 1200 Å with a power-law spectral index of -1.76, which is even somewhat flatter and more energetic than that reported by Zheng et al. In addition, the rest-frame He IIλ1640 composite equivalent width reported by Telfer et al. is only 1.45 Å, which is significantly lower than the value of 4.5 Å given by Zheng et al. This large downward revision (involving the same authors for the two papers) may be understood from noting another equivalent width entry in the Telfer et al. tabulation. They separated out a "broad feature $\sim$ 1600 Å" for an independent measurement, apparently recognizing the significance of Fe II contamination or other factors.

For the Telfer et al. composite spectrum, the analytic expression of equation (4) above gives $EW(\lambda 1640) < 1.6$ $\AA$, which is quite close to their revised measurement of 1.45 Å. From consideration of simple photoionization model calculations, Telfer et al. also noted this similarity. In addition, the problems pointed out by Eastman et al. (1983) and Netzer (1985), whereby the overall energy emitted in lines appeared to be significantly more than that available in the ultraviolet continuum (see above), are removed for the most part by the new continuum measurements, as well as by improved understanding of a significant role for dust extinction in altering relative emission-line intensities.

4. CAVEAT

Whereas the energy budget problem has been significantly diminished, as a result of improved measurements and knowledge, there are still apparent discrepancies between the latest near-ultraviolet or soft X-ray continuum observations and the energy requirements of theoretical photoionization models, as necessary to account for all of the broad emission lines.

Laor et al. (1997) illustrated (their Fig. 6) the relationship between composite *HST* quasar ultraviolet spectra and composite *ROSAT* soft X-ray continuum measurements. For this plot of $log(\nu L_\nu)$ versus $log(\nu)$, it appears that the near-ultraviolet and soft X-ray power-law continua may be smoothly linked across the unobserved far-ultraviolet spectral region. On the other hand, Laor et al. also showed (in the same figure) a postulated ultraviolet continuum as required to account for quasar emission lines (Mathews and Ferland 1987), which resembles a much more energetic (than the observations) power law with an exponential cutoff. The latter is virtually identical to the ionizing spectrum derived by Koratkar and MacAlpine (1992), as required to produce relative emission-line intensities (e.g., He IIλ1640/C IVλ1549) in a fully developed photoionization modeling analysis for the Seyfert galaxy NGC 3783. Evidently, sophisticated photoionization models, which take into account spatially varying gas densities and radiation fluxes, still appear to require more energetic ionizing radiation than is directly observed.

5. CONSIDERATION OF POTENTIAL REMAINING ENERGY BUDGET PROBLEMS

There are various possible ways of attempting to reconcile observations for the ionizing continuum radiation with apparent remaining energy discrepancies suggested by the line-emitting gas. As noted above, corrections for dust extinction within our Galaxy and for intervening gas have already been taken into account for the composite *HST* spectra published by Zheng et al. and by Telfer et al. However, one could still postulate that the line-emitting gas sees a harder ionizing spectrum compared with observations, the latter having been affected by dust or outflowing gas that is *local* to the source.

The existence of dust in or near quasars is now generally recognized (e.g., MacAlpine 1985, Malkan et al. 1998), but its influence on the observed continuum radiation remains questionable. Laor and Draine (1993) have indicated that dust obscuration should peak significantly in the 700–800 Å region, but resultant effects that could be expected from this kind of extinction law are not seen in the *HST* composite continuum spectra. Therefore, it would appear that local dust extinction probably does not play a major role in altering or softening the observed continua.

Eastman et al. (1983) investigated potential continuum altering effects that could result from absorption in $Ly\alpha$, $Ly\beta$ and the *Lyman continuum*, caused by many locally outflowing, marginally-optically-thin gas cloudlets. It was found that, for an appropriate (relativistic) velocity distribution, such cloudlets could indeed cause energetic ultraviolet continua like those postulated by Mathews and Ferland (1987) and by Koratkar and MacAlpine (1992) to appear as significantly steeper power-laws, like the observed composite *HST* spectra. This process would also account for the notable, observed power-law inflections at the rest-frame $Ly\alpha$ wavelength, which are apparent in both the *IUE* and *HST* continuum spectra. A possible problem with this explanation is that local (to the quasars) absorbing gas could also be expected to produce reemission back into the line of sight, with predictable spectral characteristics, as illustrated by Eastman et al. This is not clearly present (but also not ruled out) in the continuum observations.

It would be particularly helpful for understanding potential alterations of the ultraviolet continuum if there were a means for predicting the *intrinsic* emission at various ultraviolet wavelengths. This was part of the motivation for a detailed study by Eastman and MacAlpine (1985) of the radiative transfer for He II $Ly\alpha$ emission in quasars and the consequent prediction of ultraviolet Bowen resonance-fluorescence (Bowen 1924) line intensities. If these lines can be accurately calculated and measured, then we would have a better understanding of differential obscuration along the line of sight to the line-emitting gas. In this regard, it is notable that Telfer et al. (2002) reported the detection of an emission feature in their *HST* composite quasar spectrum, which they tentatively identified as the O III Bowen fluorescence line at λ703. This line was not actually measured by the authors, but examination of the spectrum and reported measurements for other nearby features suggest that the flux ratio for

O IIIλ703/He IIλ1640 is roughly unity, which would imply that the flux ratio for O IIIλ703/He IIλ4686 is roughly 8–10 for gas densities that could be expected in quasar broad-line regions (see MacAlpine et al. 1985). This latter line ratio was predicted by the Eastman and MacAlpine models (see their Fig. 7) to be roughly 6 for calculations with a ν^{-2} ionizing radiation power law, or roughly 1 for calculations involving a ν^{-1} ionizing continuum; and it is relatively independent of other modeling parameters. These numbers, with no allowance for local quasar dust extinction between λ703 and λ1640, seem to suggest that the ultraviolet radiation has *not* been diminished by intervening material. On the other hand, these estimated line ratios from the observations are very uncertain, and perhaps the most that can be said at present is that better measurements of the Bowen fluorescence lines could provide a valuable avenue for further investigation.

If the intrinsic ionizing radiation field seen by the line-emitting gas in quasars actually *is* as implied by the near-ultraviolet *HST* and soft X-ray *ROSAT* measurements, then it may be necessary to consider sources of energy input to the line-emitting gas *in addition* to the primary ionizing radiation. Example processes that have been investigated, with some success, include radiative shock fronts involving colliding cloudlets (e.g., Daltabuit et al. 1978), interactions involving suprathermal particles and ambient emitting gas (e.g., Ptak and Stoner 1973), and turbulent dissipative heating (e.g., Bottorff and Ferland 2002).

6. SUMMARY

During the 1980s and well into the 1990s, larger than order of magnitude energy budget discrepancies appeared to exist between the observed ultraviolet continua and emission-line measurements for quasars and Seyfert galaxies, in the sense that the observed ionizing radiation was insufficient to account for He II line equivalent widths as well as for the overall energy emergent in the lines. Today, these problems have been considerably alleviated, primarily because of improved observational data and correction procedures for both the continuum and the lines. Using composite *HST* quasar ultraviolet continua, which have been corrected for Galactic extinction and line-of-sight gas obscuration, as well as more accurate He II line measurements which allow for contamination from prevalent Fe II emission, it appears that there may be approximately enough energy in the continuum to balance the energy budget. Of course, this assumes that the gas covering factor is not *much* less than 0.1, which is still a possibility to be considered.

It may be more useful to investigate individual sources, rather than composite spectra, when considering quasar energy budgets, because the continuum slopes and line intensities appear to vary significantly from object to object. Also, further consideration of the O IIIλ703 Bowen fluorescence line and its implications regarding differential obscuration along the line of sight to quasars could be valuable.

It is still apparent that sophisticated photoionization modeling calculations may require a significantly harder ionizing spectrum than is inferred from continuum observations, in order to account for all measured line intensities. Either the observed ultraviolet spectrum may have been altered en route to us, or there may be important sources of energy in addition to the primary ionizing radiation, which are involved in producing the broad line emission of quasars and Seyfert galaxies.

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