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# OPTICALLY THIN THERMAL EMISSION AS THE ORIGIN OF THE BIG BUMP IN THE SPECTRA OF ACTIVE GALACTIC NUCLEI

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## ABSTRACT

The nature of the "big bump," the excess of ultraviolet emission seen in many active nuclei, is a clue to the source of the energy generation in the central regions of quasars. We report observations of the Seyfert galaxy Mrk 590, which show dramatic changes in both the continuum and hydrogen lines, thus offering a clue to the origin of the "big bump." While the continuum luminosity increased by ~0.5 dex, the core of the Balmer lines increased by a similar amount, but *the broad wings of the hydrogen lines maintained constant luminosity.* If hydrogen lines are produced by photoionization, nebular theory then suggests that the core of the line arises in matter which is optically thick to the ionizing continuum, while the line wings (presumably formed nearer the central object) arise in matter which is optically thin in this continuum and which nearly fully covers the continuum source. Using the "very broad line region" (VBLR) line luminosity to establish the emission measure, we then show that emission from VBLR gas can fully account for the ultraviolet continuum if it has a temperature of $\sim 10^5$ K. The VBLR is the likely site for the soft X-ray "warm absorbing" material as well as the radio free-free emission. If the VBLR gas lies between the source of the power-law continuum and the broad line region, then photoelectric absorption of hard radiation ($h\nu \geq 50$ eV) by the VBLR can produce the type of soft radiation field inferred to strike the BLR by recent studies of Fairall 9. This results in a unified picture, in which the central source of power-law radiation is surrounded by ionized partially transparent gas (the VBLR) which reprocesses ~100 eV photons into the "big bump." This in turn is surrounded by an outer, more neutral, BLR, which produces the sharp cores of the emission lines.

*Subject headings:* galaxies: individual (Markarian 590) — galaxies: Seyfert — line profiles — radiation mechanism — X-rays: general

### I. INTRODUCTION

Understanding the origin of the radio–X-ray continuous energy distribution of active galactic nuclei (AGNs) is essential if we are to then understand the nature of the most energetic phenomenon in the universe. Such studies have revealed the presence of a "big bump" which dominates the ~1000–3000 Å continuum. The bump seems likely to be thermal reemission of some sort, and could be either an optically thick accretion disk (Malkan and Sargent 1982) or merely optically thin hot gas (Antonucci and Barvainis 1988). Which is the case has major implications for the origin of the AGN phenomenon.

The presence of variability can be exploited as a tool to probe the thermodynamic and kinematic state of the line- and continuum-emitting regions (see, for example, the review by Peterson 1988). In this *Letter* we describe recent optical observations of the Seyfert galaxy Mrk 590; these show a dramatic change in both the featureless continuum and profiles of hydrogen lines. These changes support the view (Antonucci and Barvainis 1988) that the "big bump" is reprocessed light emitted by a hot, optically thin plasma within the broad line region (BLR) radius, and is likely to be the "warm absorber" deduced by recent X-ray observations.

### II. OBSERVATIONS OF MRK 590

Optical spectra of Mrk 590 were obtained with the Ohio State Image Dissector Scanner (Byard *et al.* 1981) on the 1.8 m Perkins Telescope of the Ohio State and Ohio Wesleyan Universities at Lowell Observatory (see also Peterson 1987). Details of the observations are given by Korista (1990). Dramatic changes occurred, as seen in Figure 1 which shows Mrk 590 in the highest and lowest continuum states observed between 1982 October and 1988 September. Figure 1 also shows a difference spectrum, the subtraction of the low from the high states, thus isolating the variable part of the spectrum.

The broad wings of Hα have nearly canceled out in the difference spectrum, while the core is highly variable. Synthesis of the line profile as a sharp core and broader base, both Gaussian, shows that the luminosity of the broad component did not change within the observational uncertainties, despite ~0.5 dex changes in the continuum and line core. The sharp cores *did* change, as expected from conventional BLR theory (see, for example, Shields 1979; Mathews and Capriotti 1985; Osterbrock and Mathews 1986), although the line fluxes actually changed by a *larger* fraction than did the continuum. The Hα profiles, expanded in Figure 2, show clearly that the line wings are constant even as the line core strength undergoes dramatic changes.

We used the variable part of the line (the lower panel of Fig. 1) as a template to remove the residual, variable line core from the low-state spectrum. The fractional contribution of the template was varied to produce the smoothest possible residual. The resulting component is nearly Gaussian, with a FWHM of $10^4$ km s$^{-1}$, displaced redward of the centroid of the sharp component (which is within ~100 km s$^{-1}$ of the systematic velocity) by $\sim 10^3$ km s$^{-1}$. We refer to the origin of this component as the "very broad line region" (VBLR).

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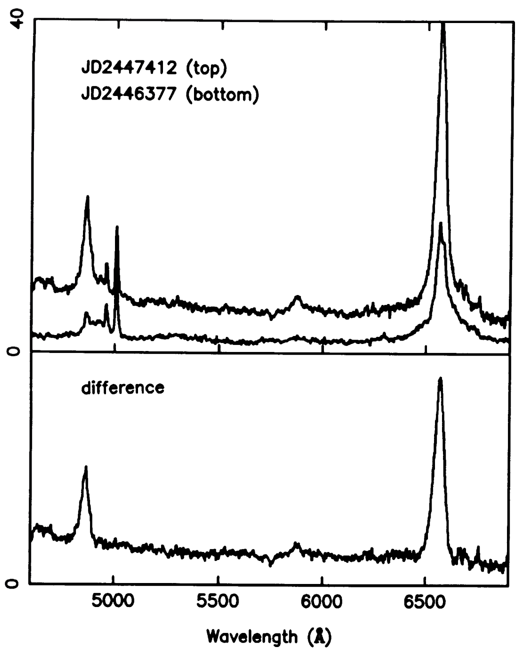

FIG. 1.—OSU IDS spectra of Mrk 590 (*top panel*) taken on 1985 November 8 = JD 2,446,377 (low state) and on 1988 September 8 = JD 2,447,412 (high state). The lower panel shows the variable part of the spectrum, obtained by subtracting the low-state spectrum from the high-state spectrum. The starlight contribution to the spectra has been removed by subtraction of a suitably scaled spectrum of M32. The spectra have been scaled to absolute units by assuming that the [O III] λ5007 flux, which has been determined by observations under photometric conditions, is constant over the time scales of interest.

## III. THE ORIGIN OF THE "BIG BUMP"

Here we outline evidence that absorbing ionized gas lies between the central source of ionizing radiation and the BLR.

### *a) The X-Ray "Warm Absorber"*

Many low-luminosity AGNs show evidence of low-energy X-ray absorption modeled as photoelectric absorption by cold neutral gas with a column density of order $N \epsilon\, dl \approx 10^{20}$–$10^{23}$ cm$^{-2}$, where $N$ is the total hydrogen density and $\epsilon$ is the filling factor (Osterbrock 1988; Mushotzky 1984; Turner and Pounds 1989). Although the measured column density is actually small for Mrk 590, $N \epsilon\, dl \approx 2 \times 10^{20}$ cm$^{-2}$ (Turner and Pounds 1989), here we discuss implications of typical absorbing column densities for properties of AGN. We conclude that the absorbing gas is likely to be both dust-free and ionized.

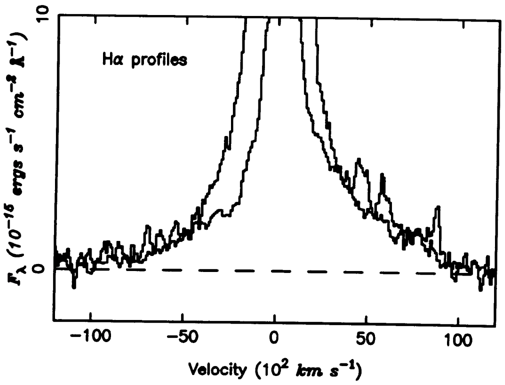

FIG. 2.—The high-state and low-state Hα profiles are expanded to show the constant very broad component.

It is clear that typical absorbing gas must be fairly dust free; for a Galactic dust-to-gas ratio, $E(B-V) \approx 1.72 \times 10^{-22}$ $N \epsilon\, dl$ (Savage and Mathis 1979), and for the range of column density given above, reddenings of $E(B-V) \approx 0.02$–$20$ would result. Although the actual extinction to an individual AGN is difficult to assess, the evidence support small values [$E(B-V) \leq 0.2$; DeZotti and Gaskell 1985], and there is no evidence for a correlation between the reddening and the deduced column density. This suggests that in general the absorbing material is fairly dust-free.

The fact that the line of sight to the central object is optically thin to Rayleigh scattering and hydrogen photoelectric absorption suggests that the X-ray–absorbing gas is ionized. The Rayleigh scattering opacity at 1232 Å is $1.7 \times 10^{-22} N_{\mathrm{H}^0}$ cm$^{-1}$ (Gavrila 1967), so if the line of sight at this wavelength is transparent, then we have the limit $N_{\mathrm{H}^0} \epsilon\, dl \ll 6 \times 10^{21}$ cm$^{-2}$. In the case of NGC 4151, X-ray data suggest a variable column density of $N_{\mathrm{H}}\ \epsilon\ dl \approx 10^{23}$ cm$^{-2}$ (Barr *et al.* 1977; Holt *et al.* 1980), while *IUE* observations reveal no evidence of extinction at $\sim$1230 Å (Penston *et al.* 1981), suggesting $N_{\mathrm{H}^+}/N_{\mathrm{H}^0} > 17$. This limit rules out BLR clouds as the source of the X-ray absorption (cf. Ferland and Mushotzky 1982), since these clouds are predominantly neutral (Rees, Netzer, and Ferland 1989). Another limit could be placed by Lyman-limit data; if those objects with typical X-ray column densities ($\sim 10^{21}$–$10^{22}$ cm$^{-2}$) are also optically thin at 912 Å, (i.e., $N_{\mathrm{H}^0} \epsilon\, dl < 1.5 \times 10^{17}$ cm$^{-2}$) then we have the more stringent limit $N_{\mathrm{H}^+}/N_{\mathrm{H}^0} > 10^4$.

Other evidence for the presence of a warm absorber in AGNs is summarized by Yaqoob, Warwick, and Pounds (1989), Nandra, Pounds, and Stewart (1990), and Pan, Stewart, and Pounds (1990).

### *b) The Continuum Incident on BLR Clouds*

Analyses of the spectral variations in Fairall 9 (hereafter F9) reported by Clavel, Wamsteker, and Glass (1989) show that the continuum incident on BLR clouds is surprisingly soft. From the behavior of the Lyα/C IV λ1549 flux ratio, Binette *et al.* (1989) and Clavel and Santos-Lleo (1990) conclude that the continuum striking BLR clouds peaks near 20 eV, and that little radiation is present at $h\nu \geq 50$ eV. The inference that the continuum striking BLR clouds is soft is, at face value, in serious conflict with the observational fact that both ultraviolet and X-ray continua are observed. The F9 observations show that it is not correct simply to join these continua smoothly.

A possible solution to this apparent paradox is that the intrinsic continuum is indeed a smooth single-index power law, but that absorption of hard ultraviolet radiation occurs between the central object and the BLR (Halpern 1984; Ferland and Rees 1988; Lightman and White 1988). Line widths suggest that it is at least plausible that the VBLR may be located at this intermediate position. An ionized hydrogen and helium plasma can be transparent to relatively soft radiation (i.e., $h\nu \leq 50$ eV) but absorb effectively at relatively high energies (i.e. $50 \leq h\nu \leq 500$ eV). Energy conservation then demands that this absorbed radiation be reemitted in other spectral ranges, while thermodynamics demands that typical photon energies decrease. The radiation which is deduced to be "missing" from the continuum in F9 will be reemitted as relatively soft radiation (i.e., the "big bump").

### *c*) *Thermal Reemission*

The absorbing gas described above must reemit radiation if energy is to be conserved.

#### i) *Free-Free Radio Continuum*

Antonucci and Barvainis (1988) and Barvainis (1990) find evidence for a component of optically thin free-free radio emission in the very luminous, radio-quiet quasar PG 1634+706. The luminosity of the "big bump" agrees well with the extrapolation of this radio continuum into the ultraviolet. The fact that the radio-emitting plasma is optically thin to free-free absorption leads to an estimate of the radius of the emitting region which is independent of the filling factor; they find $R \approx 10^{20}$ cm. The observations of Mrk 590 described above strongly support this picture.

#### ii) *The Mrk 590 Observations*

The variations, and lack of them, observed in Mrk 590 offer clues to the physical conditions in the line- and continuum-emitting gas. In general, photoionized clouds can be simplified into two geometries; radiation-bounded (optically thick in the ionizing continuum, with a resulting hydrogen ionization front) or matter-bounded (fully ionized clouds which are optically thin in the ionizing continuum). Intensities of recombination lines from radiation-bounded clouds follow changes in the ionizing continuum with some phase lag, while intensities of lines from matter-bounded clouds are proportional to their emission measure and tend to maintain constant luminosity. (This is not true for collisionally excited lines, or the diffuse continuum emitted by such clouds.) Thus a possible test of a matter-bounded versus a radiation-bounded geometry is the response of recombination lines to changes in the continuum.

The data presented here suggest that the Balmer-line profiles can be simplified into two components, a sharp core which responds to changes in the underlying continuum, and broad wings which maintain a nearly constant luminosity. The fact that the core varies with the continuum suggests that lower velocity material is radiation-bounded, an inference which is consistent with current models of the origin of BLR emission (Rees, Netzer, and Ferland 1989; Ferland and Persson 1989). The fact that the VBLR component is nearly constant, despite dramatic changes in the underlying continuum, suggests that hydrogen in clouds producing VBLR emission is fully ionized. This seems plausible since clouds closer to the source of ionizing radiation are likely to have both a larger velocity dispersion and level of ionization than more distant clouds.

An ionized hydrogen-helium plasma emits both lines and continuum, and there are simple relationships between the two which depend only on the gas temperature, ionization, and helium abundance (Osterbrock 1988). Figure 3 shows the continuous energy distribution of Mrk 590 in the ultraviolet-optical region. The optical points are from our low-state spectrum, and *IUE* observations (images LWR 13721 and SWP 17450, obtained by C. C. Wu on 1982 July 20) are also shown. Although the optical and ultraviolet data are not simultaneous, by continuity arguments we suspect that the galaxy was probably in a low state at the time of the *IUE* observations. Both sets of data have been corrected for Galactic reddening, assuming $E(B-V) = 0.045$ mag, corresponding to the measured Galactic hydrogen column density (Turner and Pounds 1989) and a normal dust-to-gas ratio. An upper limit to the reddening of $E(B-V) = 0.11$ is derived from the total hydrogen column density measured to Mrk 590, which includes absorbing gas which may be dust-free (see § III*a*). These points are shown in the figure as open circles.

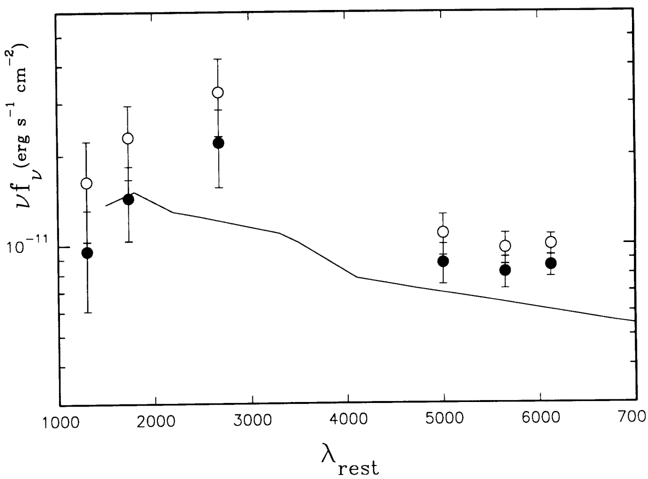

FIG. 3.—The low-state continuum energy distribution obtained from the optical and *IUE* observations. The filled circles show the measurements dereddened assuming $E(B-V) = 0.045$, which corresponds to the Galactic column (Turner and Pounds 1989). The open circles show the measurements corrected for reddening $E(B-V) = 0.11$, which is the 90% confidence upper limit to the *total* column to the nucleus of Mrk 590. The continuum from a $10^5$ K H/He plasma, normalized to the broad base of H$\alpha$, is also shown.

To within the observational uncertainties, optically thin hydrogen-helium continuous emission can account for the low-state continuum. We assume case B emissivities, a helium-to-hydrogen ratio of 10% by number, and that both H and He are fully ionized. Then, the diffuse continuum from the VBLR can be predicted from the observed VBLR H$\alpha$ intensity, with the only free parameter being the temperature of the gas. Figure 3 shows the predicted continuum for a temperature of $10^5$ K, using continuous emission coefficients calculated by Ferland (1980). In light of its simplicity, and the few free parameters available (one), the fit is surprisingly successful. Both the observed VBLR line intensity and the optical to ultraviolet continuum are consistent with optically thin hydrogen-helium emission.

#### iii) *The Emission Measure and Filling Factor of the VBLR*

A simple argument shows that the VBLR gas must be strongly clumped. The VBL component, measured from the low-state H$\alpha$ flux and corrected for a reddening of 0.045 mag, is $F(\mathrm{H}\alpha) \approx 1.0 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. For a redshift of $z = 0.0263$ and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, the resulting luminosity is $L(\mathrm{H}\alpha) \approx 1.3 \times 10^{42}$ ergs s$^{-1}$. The corresponding emission measure, assuming case B and a temperature of $10^5$ K, is then

$$\begin{aligned} E \equiv N^2 V \epsilon &= \frac{L(\mathrm{H}\alpha)}{4\pi j(\mathrm{H}\alpha)/N_e N_p} \\ &= 3.7 \times 10^{67}\ \mathrm{cm}^{-3} \approx N^2 \epsilon \frac{4\pi}{3} R^3 , \qquad (1) \end{aligned}$$

where the last term on the right-hand side assumes that the geometry is spherical.

Very rapid X-ray variability has been detected in several low-luminosity Seyfert galaxies (Pounds and McHardy 1989), although we know of no such observations for Mrk 590. If such variability is common, then the line of sight to the central object has, at most, only modest optical depth to electron scattering. Applying this limit ($\tau_e < 1$; $NR\epsilon < 1.50 \times 10^{24}$ cm$^{-2}$), the emission measure sets the limit $\epsilon < 2.6 \times 10^{-19} R$. A *lower* limit to the filling factor can be obtained from the small X-ray column density; taking $N \epsilon R \approx 2 \times 10^{20}$ cm$^{-2}$ (Turner and Pounds 1989), we find $\epsilon > 4.5 \times 10^{-27} R$. The measured absorbing column density provides only a lower limit because, if the gas is ionized as suggested above, then the X-ray opacity is diminished and the actual column density underestimated by X-ray observations.

The F9 observations, together with the greater VBLR line width, suggest that the VBLR lies within the BLR radius. Recent measurements of the response of the BLR to continuum variations (summarized by Netzer 1989) suggest that a reasonable estimate for the BLR radius in an object with the luminosity of Mrk 590 is ~50 lt-days, i.e., $\sim 1.3 \times 10^{17}$ cm. Assuming $R_{\rm VBLR} \approx 10^{17}$ cm, we obtain the limit $4.5 \times 10^{-10} < \epsilon < 2.6 \times 10^{-2}$. The deduced filling factor is small, a situation reminiscent of the BLR (Shields 1979).

### iv) *The Covering Factor*

If the VBLR does reprocess a simple power-law continuum into the "big bump," then it is possible to estimate the covering factor by comparing its luminosity with that available in ionizing radiation. The total free-free and free-bound emission by a fully ionized H-He plasma at $10^5$ K is $L_{\rm ff,fb} \approx 115 L({\rm H}\beta)$, and the *total* luminosity of the gas is about twice this. Assuming the H$\alpha$ luminosity quoted above, case B, and that the total luminosity is ~200 times greater than $L({\rm H}\beta)$, we find the total luminosity of the VBLR to be $\sim 8 \times 10^{43}$ ergs s$^{-1}$, with an uncertainty of roughly a factor of 2.

The X-ray flux at $\nu \approx 10^{18}$ Hz ($\nu f_\nu = 1.7 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$; Turner and Pounds 1989) and that at 6120 Å in the low state ($\nu f_\nu = 8.5 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$), together with the distance quoted above, suggest a power-law continuum of the form $F_\nu \approx 3.6 \times 10^{41}\, \nu^{-0.9}$ ergs s$^{-1}$ Hz$^{-1}$. If we assume that, in the low state, the incident continuum is absorbed between 912 Å and an energy $\nu_{\rm hi} \sim 2$ keV, then

$$L_{\rm absorb} = \frac{\Omega}{4\pi} \int_{912}^{\nu_{\rm hi}} F_\nu(\nu) d\nu$$

$$\approx 9 \times 10^{43} \frac{\Omega}{4\pi} \left[ \frac{(\nu_{\rm hi}/\nu_{912})^{0.1} - 1}{0.647} \right] {\rm ergs\ s^{-1}} , \qquad (2)$$

where $\Omega/4\pi$ is the VBLR covering factor. Within the observational uncertainties, *in the low state the ionization of the VBLR can be sustained only in coverage is nearly complete* ($\Omega/4\pi \sim 1$), *and nearly all ionizing radiation is absorbed.* In the high state, the underlying power-law continuum will be ~0.5 dex brighter; as a result, the VBLR gas will be more highly ionized, hotter, and more transparent to low-energy ($h\nu \leq 50$ eV) photons. The transmitted continuum would then be much like that deduced for F9 (Clavel and Santos-Lleo 1990). This variable UV transmission of the VBLR may account for the fact that the core of the line changed by *more than* the optical continuum.

## IV. DISCUSSION

We have presented evidence that a component of gas, which we refer to as the "very broad line region" (VBLR), exists between the central source of ionizing radiation and the BLR. This gas is highly ionized and seems likely to be the "warm absorber" of soft X-ray absorption observed in certain low-luminosity objects, the "big bump" observed in the ultraviolet of most AGN, and the radio free-free continuum observed by Antonucci and Barvainis (1988). This VBLR acts as a filter, altering the transmitted continuum, by removing ~50–500 eV radiation, and reprocessing it into softer radiation, predominantly the big bump (Ferland and Rees 1988 and Lightman and White 1988 show specific examples of such effects for another geometry).

Mrk 590 is not the only AGN for which a variable core is superimposed on nearly constant wings. Observations of Ly$\alpha$ and C IV $\lambda$1549 higher luminosity QSOs show that the emission-line cores are much more variable than the line wings (Gondhalekar 1987, 1990; O'Brien, Zheng, and Wilson 1989; Pérez, Penston, and Moles 1989).

This interpretation of the origin of the "big bump" differs with the conventional one, in which it is due to an accretion disk (Malkan and Sargent 1982). The argument here is not over whether there is a central black hole, or whether accretion occurs in the central regions of AGN. Rather, it is over whether the bump is due to optically thin or optically thick gas. The presence of optical hydrogen emission lines, and free-free emission in the radio, both suggests that the emitting region is optically thin.

Our picture explains why the big bump is less variable than the X-ray continuum, but this is not to say that no variability is expected at all. Changes in the intrinsic power-law radiation field produce changes in the temperature of the VBLR; the gas will tend to grow hotter as the underlying continuum brightens. This has little effect on intensities of the hydrogen lines (their emissivity is proportional to $\sim T_e^{-1}$) but will have major effects on collisionally excited lines, as well as the ultraviolet intensity of the "big bump," since both have exponential temperature dependences.

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