What’s Emitting the Broad Emission Lines?

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Abstract. I present a brief review about our ideas concerning the origin and nature of the broad line emitting gas. This is one of the outstanding problems in quasar research. I suggest the establishment of a central data base of high quality quasar spectra as a means to realize an understanding of quasars.

1. Introduction

Question: What is the broad line region (BLR), that is, what would we see if we could image it? Answer: Nobody knows. Since the identification of their emission lines by Schmidt in 1963 we have wondered about this question. It is disturbing that the origin of the line emitting gas remains to this day a large question mark. There is no single working model. Our only framework from which to begin our understanding is this: gas of unknown origin, with particle densities comparable to those in the solar chromosphere, lies distributed and moves within the gravitational potential of a central supermassive black hole (Blandford & Rees 1978; Rees 1984), and is photoionized by the central ionizing continuum source (Davidson & Netzer 1979). The gas elemental abundances in even high redshift quasars is at least solar (Hamann & Ferland 1993; Hamann & Ferland 1999; Hamann, these proceedings). But what the emitting gas is doing and how it got there remain only loosely constrained.

I review briefly the various models, ideas (§ 2), and few constraints (§ 3) concerning the origin and nature of the broad line emitting gas (BLEG). In § 4 I sum up the current situation, and suggest the importance of the establishment of a central data base of high quality quasar spectra as a means to realize an understanding of quasars — drawing parallels to our understanding of stars and their spectra beginning one century ago.

2. The Ideas

Most of our ideas concerning the nature of the BLEG center around three possibilities: clouds, accretion disks, and stars. Some models invoke combinations or hybrids of these three. I will discuss each of these in turn.

\textsuperscript{1}The angular diameter of the best studied BLR, that belonging to NGC 5548, is \( \sim 0.2 \) milliarcseconds.
2.1. Clouds

Here I define a cloud to be a localized, non-self-gravitating entity such as that found in the interstellar medium (ISM), existing independently from accretion disks or stars. Debris from disks or stars are discussed in their own sections below. As will become apparent, the cloud models suffer from a variety of problems, especially those involving pressure equilibrium (confinement) and dynamical stability, and thus may be transient \( \tau_{\text{life}} \leq \tau_{\text{dyn}} \) entities if they can exist at all.

One of the more popular cloud models (McCray 1979; Krolik, McKee, & Tarter 1981) had its origins with the old two-phase equilibrium scenario of the local Galactic ISM (Spitzer 1978). The clouds are “cold”, dense \( (\sim 10^{10} \text{ cm}^{-3}) \) condensates in pressure equilibrium within a hot \( (T \approx 10^{8} \text{ K}) \), low density flow. This hot phase was proposed to be in Compton equilibrium with the quasar radiation field. However, Mathews & Ferland (1987; MF87) punched several holes into this picture. First, it was determined that the quasar radiation field’s Compton temperature is only \( \approx 10^{7} \text{ K} \) (see also Fabian et al. 1986), far too low for the clouds to be stable, or for the hot phase to be optically thin to X-ray radiation. Second, even if the hot phase temperature were \( 10^{8} \text{ K} \) drag forces would impose a terminal velocity on the clouds far too small to account for the emission line widths. These problems could be overcome if the temperature of the intercloud medium exceeded \( 10^{9} \text{ K} \), a relativistic wind. However, MF87 also suggested that the cold-phase cloud condensation process could be disrupted by various strong radial forces present in the quasar environment. Internal line radiation pressure can also be disruptive of clouds (Elitzur & Ferland 1986). A good review of the “cloud” stability problem is given in Mathews & Capriotti (1985).

Radiatively accelerated pancake clouds and clouds oscillating about an equilibrium radius (gravitational vs. radiative accelerations) in an unspecified confining quasar atmosphere have been proposed by Mathews (1982; 1993). To obviate the requirement of a Compton heated medium, Martin Rees (1987) proposed that the clouds could be magnetically confined \( (B \sim 1 \text{ Gauss}) \), similar to the situation in the filaments of the Crab Nebula.

Confinement and stability problems aside, a number of investigators have attempted to set limits on the minimum numbers of clouds required to produce the observed smooth emission line profiles. The simulations of Capriotti, Foltz, & Byard (1981b) coupled with medium S/N ratio and spectral resolution observations of Atwood, Baldwin, & Carswell (1982) placed the lower limit at \( N_{cl} > 5 \times 10^{4} \). This estimate assumed a simple local line profile with a thermal width corresponding to a temperature \( T \approx 10^{4} \text{ K} \). Arav et al. (1998a,b) used the power of the Keck I 10m telescope and a spectral resolution of 6 km/s, with a similar cross-correlation analysis but more sophisticated simulations of possible local line profiles, to push the lower limits to \( N_{cl} > 3 \times 10^{7} \), given certain assumptions. A question that arises immediately is what process could give rise to so many clouds? The lower limit could be as small as \( N_{cl} > 3 \times 10^{5} \) if the local line widths are significantly larger than 80 km/s. The lower limit to \( N_{cl} \) diminishes with increasing local line width. This question of cloud number also applies to the scenario involving illuminated clumps of disk debris (§ 2.2), stars (§ 2.3), or any that involves clumpy, localized emission entities.
2.2. Accretion Disks & their Debris

Given that the quasar paradigm involves a disk of matter accreting onto a supermassive black hole, with the inner regions emitting the optical – X-ray continuum (Rees 1984), a minimalist approach would put the line emitting gas in the outer regions of the accretion disk. Nature already does this in stellar cataclysmic variable systems. The existence of cool, high column density material in the vicinity of the X-ray continuum source is supported by observations in Seyfert 1 nuclei of hard X-ray reflection humps and broad iron Kα emission lines near 6.4 keV, whose line profiles obtained by ASCA can be fitted well by some accretion disk models (Tanaka et al. 1995; Fabian et al. 1995; Mushotzky et al. 1995; Iwasawa et al. 1996; Nandra et al. 1997; Reynolds et al. 1997). These reflection components are rarely observed in quasar spectra, however. A further advantage of a disk like geometry is that the probability of one or more broad line emitting entities lying along the line of sight becomes small for random orientations, and very few quasars or AGN show evidence of “cold” X-ray absorption, expected from a typical broad line “cloud”. Finally, there is no confinement problem for gas associated with accretion disk, and the gas reservoir is large. The primary drawback of the accretion disk scenario is that at present its structure and mechanism for energy dissipation are not well understood. Most models of accretion disk structure are based upon the work of Shakura & Sunyaev (1973). See Blandford (1985), Begelman (1985), and Frank, King, & Raine (1992) for good reviews.

Illuminated Disks. Hard X-ray illumination of the outer regions \(10^2 R_g < r < 10^4 R_g\); here \(R_g = 2GMbh/c^2\) of the accretion disk has been proposed by Collin-Souffrin and co-workers (Collin-Souffrin, Hameury, & Joly 1988a; Dumont & Collin-Souffrin 1990; Rokaki et al. 1993) as a means to account for the low ionization broad emission lines: Balmer lines, Mg II 2800, and the forest of Fe II lines. These lines are powered via the hard X-ray heating of the dense \(n_H \sim 10^{12-14} \text{ cm}^{-3}\), high column density \(N_H > 10^{25} \text{ cm}^{-2}\) medium. Under these conditions, the emission is not particularly sensitive to the structure of the lower “chromosphere” of the disk where these lines are emitted. However, the medium ionization (e.g., C III 1909) and high ionization (e.g., C IV 1549) lines, including Lyα, derive their energy from softer ionizing photons (13.6 eV – 200 eV), and their emission is very sensitive to the uncertain structure of the upper disk chromosphere, if they are emitted there at all.

Illuminated Disk Debris. Radiation pressure driven winds from accretion disks have been most recently investigated by Murray & Chiang (1997; see also Yamamoto in these proceedings). Resonance line scattering provides most of the pressure to accelerate the wind, and the gas densities are kept low to minimize the mass load of the radiatively powered wind. Substantial filtering of the soft X-ray continuum must occur within “hitchhiking gas” just interior to the wind, or else the gas would be overionized and the wind would die. The bulk of the

\[2\]The geometry of the innermost accretion disk and the X-ray emitting continuum source are not understood, thus the mechanism governing the X-ray illumination of the disk is not well constrained.
broad line emission occurs in regions near the base of the wind close to the disk surface where the wind radial velocity component is small compared to the disk Keplerian velocity component, but the radial and rotational velocity shears are large. These shears induce anisotropic photon escape probabilities, and the radial shear component can produce singly peaked emission lines even though the velocity field is dominated by Keplerian rotation. The particle densities of the line emitting gas range from $10^7 \text{ cm}^{-3}$ to $10^9 \text{ cm}^{-3}$, much lower than all other modern models of the BELG and their spectra (e.g., Ferland et al. 1992). A possible shortcoming is that such gas is unlikely to produce the observed Balmer lines, Mg II λ2800, or the Fe II spectrum. This model has not yet been computed self consistently (true enough of all dynamical BELG models) in that the gas temperature, ionization, and optical depths are computed as if in a static slab, whereupon the line escape probabilities are altered for single scattering within the velocity shears within the wind flow. The geometry of an accretion disk wind with central and local sources of photons is not well understood, either.

Another model for disk debris is described most recently in Cassidy & Raine (1996). A nuclear wind of unspecified origin interacts with a thermally driven wind generated by accretion disk gas heated to the Compton temperature by the central X-ray source. The interface between these winds near the accretion disk generates Kelvin-Helmholtz instabilities that create dense clouds that are then accelerated in the flow before being destroyed. The velocity field of the line emitting gas is Keplerian flow dominated upon injection and takes on larger radial contributions as the cloud is accelerated in the wind. High and low ionization lines are formed in the debris. The hot wind should have temperatures of order $10^8 \text{ K}$, and if the quasar radiation field cannot do this, then some other mechanism must provide the necessary heating.

A final scenario involving debris from accretion disks has magnetically confined “clouds” centrifugally accelerated above the accretion disk (Emmering, Blandford, & Shlosman 1992; Königl & Kartje 1994; de Kool & Begelman 1995; Bottorff et al. 1997). Magnetic lines of force emanate outwards and upwards from the disk, and blobs of matter are loaded onto the field lines and then centrifugally accelerated. Once exposed to the central ionizing source these “clouds” are photoionized and produce emission lines before dissipating at the Compton temperature at high altitudes above the disk. The velocity field is cylindrical, with contributions from Keplerian and z components varying with distance along and above the disk. Given the thermal, radiation, and magnetic pressures present, the emitting entities may be shaped like spaghetti or fetuccini (Bottorff & Shlosman 1998), and both high and low ionization lines are formed in the distribution of pasta shaped clouds.

**Summary.** No model involving disks yet stands high above the others, and all suffer from our ignorance of the detailed structure of quasar accretion disks.

### 2.3. Stars & their Debris

Certainly Seyfert 1 nuclei and most and perhaps even all quasars are associated with the nuclei of galaxies (see Korista, these proceedings, for references), composed of stars and an ISM. The center of our Galaxy is a relatively active region consisting of young star clusters and very dense molecular clouds. A reasonable
question to ask is what would happen if one placed an accreting supermassive black hole down in the center of this? A number of ideas have suggested a marriage of the stellar and interstellar environment to the quasar paradigm.

**Bloated Stars.** A number of investigators have proposed “bloated stars” in one form or another for the origin of the BLEG (Edwards 1980; Penston 1988; Scoville & Norman 1988; Kazanas 1989; Baldwin et al. 1996), though it wasn’t until the work of Alexander & Netzer (1994) that the model was investigated in greater detail. The idea is that a dense star cluster lies and evolves in the vicinity of the supermassive black hole of the quasar with its source of ionizing continuum photons (Murphy, Cohn, & Durisen 1991). The cross sections presented to the illuminating continuum source by normal cluster giant or supergiant stars are insufficient to produce the observed line emission, since the expected numbers of accompanying dwarf stars would otherwise be too high to allow for a quasi-stable star cluster. So instead the stars are assumed to be “bloated” through normal stellar winds and/or those induced by the hard photon flux or even line driving (Baldwin et al. 1996). These winds are likely anisotropic, perhaps somewhat akin to “comet tails” (e.g., Scoville & Norman 1995), though this structure has never been computed fully self consistently. The enhanced cross sections are sufficient for efficient reprocessing of the continuum into the broad emission lines. Stars might also wander within the black hole’s tidal radius and be shredded (Roos 1992), but the tidal radius occurs outside the Schwarzschild radius only when the mass of the central objects is less than about $10^8 M_\odot$, unless the star’s average density is substantially sub-solar. The stars themselves are self gravitating and in any case provide a huge reservoir of gas upon which the BLEG may draw, and the work of Alexander & Netzer suggests that only $\sim 50,000$ bloated stars are required in the broad line emitting environment of a moderate luminosity quasar.

**Hybrids: Star – Disk Interaction Models.** To account for the higher ionization lines that may not be emitted in their illuminated accretion disk model, Collin-Souffrin et al. (1988b) proposed a hybrid disk/stellar debris model. A nuclear star cluster produces supernova and stellar wind ejecta that are shocked in a dense ISM and cool to moderately high densities ($n_H \sim 10^{9-12} \text{ cm}^{-3}$) (Perry & Dyson 1985; Williams & Perry 1994) in the vicinity of the quasar accretion disk. This fragmenting “stellar shrapnel” is transient and replenished by the stellar cluster, and so does not require a confinement mechanism. Another hybrid scenario for the origin of the BLEG involves the stars of a dense nuclear star cluster colliding with the accretion disk and the resulting “star tails” become the line emitting gas (Zurek, Siemiginowska, & Colgate 1994).

**Summary.** In principle, the “bloated” stars scenario should presently be on firmer theoretical footing than other scenarios for the BLEG (e.g., accretion disks), since the structure of normal stars is well understood. Even so, no self-consistent models for a stellar atmosphere’s interaction with the full quasar environment have been computed. The primary concerns of the stellar origin scenario of the BLEG have been generally related to the question of packing enough stars close enough to the quasar’s “central engine.”
3. Evidence

By now the reader should be convinced that the broad range in BLEG origin scenarios is indicative of a relative “vacuum” in the observational constraints. In addition, gaps in our understanding of some of the physics allow for a plethora of free parameters. While all true, progress has certainly been made on both fronts, especially since the advent of the solid-state detector spectrograph some 20 years ago, and with the rapid increase in computational power in the same time period. The following is a non-exhaustive review of the observational evidence that constrains the origin and nature of the BLEG.

3.1. Continuum – Line Reverberation

Since the emission lines are powered primarily or exclusively via photoionization, a time-variable ionizing continuum flux will be seen by a distant observer to reverberate throughout the BLR as time-variable emission lines. In principle the structure and dynamics of the emitting gas can then be derived (Blandford & McKee 1982; Capriotti, Foltz, & Peterson 1982; Welsh & Horne 1991; Pérez, Robinson, & de la Fuente 1992). The recovered structure and dynamics might then point to an origin of the BLEG or exclude others. However, recovery of this information via reverberation has proven difficult. Combinations of uneven, insufficiently frequent, and insufficiently extensive time sampling have hampered our efforts. An extensive literature exists on this subject and will not be reviewed here. I refer the reader to Peterson (1993; 1997) for recent reviews of the subject. A summary of the information gained concerning the BLR through these experiments is as follows. (1) The BLR is geometrically extended, and its characteristic distance from the ionizing continuum source scales as $\sim 0.1 L_{46}^{1/2}$ pc, where $L_{46}$ is the ionizing continuum luminosity in units of $10^{46}$ ergs/s. (2) The BLR is stratified in ionization, and a range of gas densities must be present. (3) Pure radial flows, inward or outward do not dominate the BLEG dynamics. Any model for the origin of the BLEG must fall within these constraints.

3.2. Emission Line Profiles

If the emission line profiles were to suggest a particular gas dynamics, this in turn might constrain the origin of the BLEG (Blumenthal & Mathews 1975; Capriotti, Foltz, & Byard 1981a). Unfortunately, the emission line profiles, characterized roughly as the functions $I_A \propto \log(\Delta \lambda)$ and/or $I_A \propto (\Delta \lambda)^{-2}$, do not point to a unique dynamical mechanism for the emitting gas, though their forms are indeed constraints on any model. Most emission lines are singly peaked, though are often accompanied by bumps or shoulders, and are often asymmetric (e.g., see Boroson & Green 1992). Also unexplained are the observed emission line peak redshift differences, sometimes exceeding $\Delta v \approx 1000$ km/s (Gaskell 1982; Wilkes 1984; Wilkes 1986; Espey et al. 1989; Corbin 1990; Tytler & Fan 1992). The higher ionization lines tend to lie at smaller redshifts, and are likely blueshifted relative to the lower ionization lines that lie closer to the quasar’s systemic redshift.

Line emission from accretion disks is expected to result in double-peaked emission lines (see Marsh & Horne 1986 for a nice review), and the paucity of such examples in Seyfert 1 and quasar spectra has been used as an argument
against an accretion disk origin of the broad emission lines (e.g., see Sulentic 1989; Sulentic et al. 1990). However, the anisotropic line radiative transfer expected in radiatively driven winds (Murray & Chiang 1997) and the 2-D velocity field nature of the magnetically driven “winds” (Emmering et al. 1992; Bottorff et al. 1997) can produce singly peaked emission lines. In any case a small number of objects (e.g., Arp 102B, 3C 390.3, 3C 332, and others) do exhibit broad, double-peaked emission lines (Chen & Halpern 1989; Eracleous & Halpern 1994; Halpern et al. 1996). These objects tend to be LINERs (“low ionization nuclear emission regions”; e.g., see Barth et al. 1998) and/or radio galaxies, usually with weak or absent UV bumps\[3\]. Generally, only the Mg II λ2800 and Balmer emission lines exhibit the double-peaked profiles. Halpern et al. (1996) argued that the lack of a double-peak signature in Lyα λ1216 in some objects indicates thermalized emission such as that expected from high density and column density gas in accretion disks. In an effort to confirm or disprove the accretion disk hypothesis for the BLEG origin of this subclass of objects, a number of studies have sought to carefully measure the emission line profiles and monitor their variations due to reverberation effects. Some of the observed profiles and their variations were unexpected based upon simple models of line emitting accretion disks (Miller & Peterson 1990; Veilleux & Zheng 1991; Zheng, Veilleux, & Grandi 1991; Sulentic et al. 1995; Eracleous et al. 1997). However, effects such as disk “hot spots” (Zheng, Veilleux, & Grandi 1991; Newman et al. 1997) or two-armed spiral waves\[4\] (Chakrabarti & Wiita 1994), or precessing elliptical disks (Storchi-Bergman et al. 1997) might explain some of the anomalies.

Three historically narrow-line emitting objects (NGC 1097, M 81, and Pictor A) recently and suddenly exhibited broad, double-peaked Balmer emission lines. It has been suggested that this could arise from the sudden appearance of the broad line region (clearing of obstruction), the tidal disruption of at least one star, or the sudden switch-on of a source of high energy photons in the presence of an established accretion disk (Storchi-Bergman et al. 1995). Their relationship to the above class of double-peak emitters is unclear.

In several objects with either double peaked or double Shouldered Balmer lines, Zheng, Binette, & Sulentic (1990), Marziani, Calvani, & Sulentic (1992), and Sulentic et al. (1995) find that the profiles and their variations are better fitted by two-stream or bi-cone subrelativistic flow models. The nature of these flows and thus of the emitting gas, however, has been left generally unspecified by these investigators.

3.3. Other Considerations

An often tacit assumption in simulations of quasar emission line spectra (e.g., Rees, Netzer, & Ferland 1989) is that the local line width is dominated by thermal gas motions. This may occur in confined or quasi-static clouds, but in most other scenarios for the BLEG the emitting gas is locally dynamic, and

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3I find it ironic that the objects that exhibit the classical double-peaked accretion disk emission line profiles lack the classical UV continuum signature of accretion disks (Shields 1978; Malkan & Sargent 1982).

4Steeghs, Harlaftis, & Horne (1997) and others have identified signatures of line emission from enhanced gas density via spiral shocks in the disks of cataclysmic variable systems.
significant local line broadening can result. This alters the diffuse emission escape probability as well as the ionization and thermal structures of the emitting gas, and a significant contribution from continuum pumping becomes possible (Shields, Ferland, & Peterson 1995). In the near future, as computers become fast enough to simulate accurately the radiative transfer of the diffuse emission, we should consider testing the effects of extra-thermal local line broadening on the computed emission line spectrum. We may be able to set some limits to the presence of velocity gradients, shears, or streams. These theoretical limits may then be tested against the emission line profile smoothness requirements from observations (Arav et al. 1998a,b), and perhaps then we can say what the BLEG is not.

One of the most interesting and promising clues from quasar emission line spectra is that they represents emission from chemically enriched gas with metallicities broadly constrained to lie within $1–10 \ Z_\odot$, even in the highest redshift sources (Hamann & Ferland 1993; Hamann & Ferland 1999; Hamann, these proceedings). Rapid star formation and evolution in dense cluster environments can account for these enrichments, although other scenarios are possible. For further discussion of quasar gas metallicity, see my other conference proceedings contribution. Any successful model for the origin of the BLEG will need to address how the enriched gas became the broad line emitting gas.

4. Summary & Comments

*Anyone who isn't confused just doesn't understand what's going on.*

— anonymous

One of the outstanding mysteries concerning quasars and active galaxies is the origin and nature of the broad line emitting gas. No model or scenario fits all the observational data, and most suffer from too few observational constraints and too many free and often ill-understood parameters.

Unless we figure out how to image the central regions of active galaxies, the continuum and emission line reverberation experiments offer the most powerful means to placing useful constraints upon the nature of the BLEG and possibly its origin. However, it will likely take a dedicated multiwavelength spectroscopic orbiting platform before we can learn anything further from reverberation.

A large majority of what we do know about quasars arises from their spectra. However, some of our observational constraints are muddied by spectra of moderate or even poor quality. **The establishment of a central data base of high quality (S/N, spectra resolution and coverage) quasar spectra** and their uniform measurements would lay a firm foundation of observational constraints upon which we can build our understanding of quasar spectra. One century ago, such a data base existed for stars (e.g., Harvard Observatory), where they were classified “zoologically” by characteristics of their spectra. However, the nature of stars and their spectra were unclear. With the dawning of the 20th century came our realization of the quantum nature of light (Planck and Einstein), the theoretical progress set forth by Saha and Eddington and others, and the identification of the stellar main sequence by Hertzsprung and Russell. The second decade gave birth to quantum mechanics
and the salient Ph.D. thesis of Cecilia Payne, and finally we understood the story of stellar spectra. The third through sixth decades saw the development of the theory of nucleosynthesis by Bethe, Gamow, then Fowler, Hoyle, and Geoffrey and Margaret Burbidge (the latter two also important investigators of quasars), and then Iben's work on stellar evolution. *Underlying all of this progress was a vast stellar spectroscopic data base.* One of the greatest accomplishments of this century has been the understanding of stars. Today we stand as we did one century ago, perhaps too, near a precipice. Will the next century bring a similar leap in our understanding of quasars and their place in the universe?

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