Reverberation Mapping of the Broad-Line Region in Active Galactic Nuclei
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Continuum and Line Variability in Nuclear Starbursts

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Abstract. It has been suggested that the activity seen in many active galactic nuclei (AGNs) may be powered solely by young stars and compact supernova remnants (cSNR) in a nuclear burst of star formation. We discuss here some of the predictions of the starburst model for AGNs regarding their continuum and line variability.

• The number of slow peaks or supernova (SN) events in the light curve of low-luminosity AGNs scales linearly with the nuclear luminosity. An AGN with $M_B(min) \approx -21.5$ produces 1 slow peak (or SN) per year. This result is independent of the initial mass function, age and/or total mass of the cluster.

• The observed line variability in AGNs is similar to that expected in rapidly radiating compact supernova remnants during thin shell formation, i.e., as it achieves maximum luminosity. This event, which has a typical time scale of a few months and involves energies of about 5% of the total explosion energy, produces time delays between the continuum and line emission, and emission-line ratios and luminosities with values similar to those observed in low-luminosity AGNs. The predicted delays range from few days for the high-ionization lines to few weeks for the low-ionization lines. Shorter flares with little or no lag between continuum and lines are also expected.

• The time-averaged equivalent width of Hβ is related to the total energy of the SN, almost independently of the initial mass function, age and/or total mass of the cluster and of the assumed cosmology; the observed constancy of the value of the equivalent width of Hβ in AGNs is the direct consequence of the universal value of the energy released in a SN explosion being about 3×10^{51} ergs.

1. Introduction

The origin of the observed continuum and line variability of radio-quiet AGNs, i.e., Seyfert galaxies and most optically selected quasars, is a central problem that must be explained by any model. The best information regarding variability in AGNs is provided by observations of a small group of nearby low-luminosity type 1 Seyferts. The light curves of many type 1 Seyferts show two distinct components: an occasional sharp peak superimposed onto a long-term recurrent modulation (Lyutyi 1977, 1979; Dibaĭ & Lyutyi 1984; Lyutyi et al. 1984; Smith et al. 1991), hereinafter called rapid and slow components, respectively (see

Smith et al. 1991 for a schematic picture). The peaks of the rapid component last some weeks, while the cycles of the slow one are a few years long.

In what has become known as the starburst model, the observed variability of radio-quiet AGNs is postulated to be produced by the SN and cSNR activity resulting from the evolution of a metal-rich massive stellar cluster, the product of a starburst in the core of an early-type galaxy (Terlevich et al. 1987, 1992). The multifrequency spectrum of these radio-quiet AGNs can be reproduced by the combined contribution of stars, SNe, cSNRs, and dust present in a stellar cluster 10 to 60 Myr old (Terlevich 1990). Most of the optical/UV (the big UV bump) and bolometric nuclear luminosity is provided by the young stars, while the cSNRs are responsible for the observed nuclear variability and characteristic broad-line spectrum. The broad lines observed in type 1 Seyferts and QSOs are produced in cSNRs by the interaction of the ejecta of SNe with a high-density circumstellar medium. The broad lines, typical of AGNs and preferentially detected in the cores of big spheroids, are assumed to be related to the high metallicity of the core stars. This high metallicity leads to large mass-loss rates that in the high-pressure ISM typical of starbursts produces high circumstellar densities around the cSNR progenitors. The intrinsic parameters of the broad-line region (BLR) can be obtained from theoretical models of cSNRs (Terlevich et al. 1992), while the observed delays of the response of the broad emission lines to the variations of the continuum are well explained by thermal instabilities during shell formation in cSNRs (Tenorio-Tagle et al. 1992). The observational data that more strongly support the cSNR origin of the BLR and its variability, are the properties of the "Seyfert 1-like" supernovae SN 1987F and SN 1988I (Filippenko 1989), SN 1983K (Terlevich & Melnick 1988), and SN 1988Z (Stathakis & Sadler 1991). Terlevich & Boyle (1993) have explored the hypothesis that QSOs are the young cores of massive ellipticals forming at $z \geq 2.0$. They found that only a small fraction ($\sim 5\%$) of the total mass of elliptical galaxies, the core mass, is needed to participate in a burst to explain the observed luminosities and luminosity function of QSOs at $z \geq 2.0$. Recent work on the metal content of QSOs (Hamann & Ferland 1993) supports the hypothesis that these systems are associated with a metal-rich environment similar to that found in the cores of elliptical galaxies.

We will discuss the following important relations regarding the variability of AGNs in the starburst model:

1. The supernova rate (or number of peaks of the light curve) and its relation to the blue-band stellar luminosity.

2. The equivalent width of Hβ and its relation to the average energy per SN event.

3. The variability and its relation to the core luminosity of low-luminosity AGNs.

We briefly review the time-dependent process that occurs prior to thin shell formation in a rapidly radiating supernova remnant, i.e., as it achieves maximum luminosity. This process, which has a typical time scale of a few weeks and involves energies of about 5% of the total explosion energy, produces time delays between the continuum and line emission and emission-line luminosities with values similar to those observed in low-luminosity AGN.

2. Estimation of the Supernova Rate in Young Clusters

In the starburst model, the slow component of AGN continuum variability is related to the long-term behavior of cSNR, while the rapid component is mostly due to cooling instabilities in the shells of cSNRs and to SN flashes. A double-peak variation is expected in the light curve of a SN evolving in a high-density circumstellar medium, the first peak corresponding to the SN flash, and the second one to the time when the cSNR reaches the maximum of its radiative phase (Wheeler et al. 1980; Shull 1980; Terlevich et al. 1992). The typical time scale of the radiative phase is,

$$t_{\rm sg} \approx 0.62\, \epsilon_{51}^{1/8} n_7^{-3/4}\ {\rm yr}, \tag{1}$$

where ϵ_{51} is the energy of the cSNR in units of 10^{51} ergs and n_7 is the circumstellar density in which this cSNR evolves, in units of 10^7 cm^{-3}. During the radiative phase, the luminosity of the remnant can be approximated as,

$$L_{Bol}(t) \approx 10^{10}\, \epsilon_{51}^{7/8} n_7^{3/4} \left(\frac{t}{t_{\rm sg}}\right)^{-11/7} {\rm L}_\odot \quad , \tag{2}$$

and is emitted mainly in the far UV and X-rays. Aretxaga & Terlevich (1994; hereafter AT) have shown that cSNR-type events can account for the slow-component variations in the well-sampled light curve of NGC 4151, both in energy and time scale of the process, and have estimated the number of cSNRs required to explain the luminosity of the nucleus of an AGN.

AT calculated the specific supernova rate $\nu_{\rm SN}/M_{\rm t}$ and specific blue luminosity $L_{\rm B}^\star/M_{\rm t}$, for a variety of initial mass functions (IMFs) using stellar evolutionary models from Maeder (1990). It was found that both parameters decrease with increasing age of the cluster and are similarly dependent on the assumed IMF. A very important consequence of this finding is that the ratio of the supernova rate per unit mass to the blue luminosity per unit mass, $(\nu_{\rm SN}/M_{\rm t})/(L_{\rm B}^\star/M_{\rm t}) = \nu_{\rm SN}/L_{\rm B}^\star$, i.e., the supernova rate per unit stellar blue luminosity, is almost independent of the assumed IMF and is basically constant over the whole SN II phase. This is because both quantities, the SN rate and the blue luminosity, depend mainly on the number of stars in a narrow mass range close to the turn-off point, and do not depend on the number of low-mass stars that are the bulk of the mass of the cluster. Table 1 gives the SN rate as a function of the absolute blue magnitude of the stars of the cluster, and some other relevant ratios for a range of cluster ages and IMFs.

The main result is that a young cluster with age between 10 and 60 Myr and with $M_B(min) \approx -21.5$ produces 1 SN per year, almost independently of the assumed IMF.

3. Variability in Very Low-Luminosity AGNs

Due to the stochastic nature of the SN activity and the low SN rate in low-luminosity AGNs, the nucleus can go through transient quiescent phases when any light from the cSNR is faint, and consequently no broad lines are detected even though the continuum is still blue due to the presence of hot stars. This

Table 1. Description of the cluster evolution

t_7 (1)	M_B^* (2)	ν_{SN}/L_B^* (3)	L_B^*/M_t for $\alpha = 2.35$: $m_l = 0.3$ M$_\odot$ (4)	$m_l = 1$ M$_\odot$ (5)	$m_l = 3$ M$_\odot$ (6)	M_{SN} (7)
1.0	−21.7	0.15	28.70	48.80	78.00	19.8
2.0	−21.5	0.17	17.10	29.10	43.40	12.1
3.0	−21.3	0.21	12.80	21.70	30.60	9.8
4.0	−21.3	0.21	11.00	18.60	25.10	8.4
5.0	−21.3	0.21	9.44	16.00	20.50	7.6
6.0	−21.4	0.18	8.78	14.80	18.60	6.9

(1) Time, in units of 10^7 yr.
(2) Absolute blue luminosity of a cluster with a SN rate of 1 per year
(3) Ratio of SN rate to stellar blue luminosity, in 10^{-10} yr^{-1} $L_{B\odot}{}^{-1}$
(4 – 6) Ratio of stellar blue luminosity to total initial mass of the cluster for several power-law IMFs of slope $\alpha = 2.35$ and lower mass limits (m_l), in solar units
(7) Initial mass of the stars undergoing explosion, in solar units.

is likely to be the case for the deep photometric minima of 1981 and 1984 in NGC 4151 during which the nucleus resembled a type 2 Seyfert (Antonucci & Cohen 1983; Penston & Pérez 1984; Lyutyi et al. 1984; AT). This characteristic of the SN activity gives a simple explanation for the transient stages of type 2 Seyfert nuclei observed as LINERS and type 1 Seyfert nuclei.

One important prediction of the starburst model for AGNs is that the variability amplitude observed in broad-line AGNs should reach a maximum for those nuclei with luminosity similar to the maximum luminosity of cSNRs, i.e., $M_B \approx -20$. AGNs with higher luminosities should show a lower amplitude of variability due to the superposition of cSNR events, while lower-luminosity AGNs, i.e., those with $M_B \gg -20$ (LLAGNs) should also show a smaller variability amplitude due to old and less luminous cSNRs which evolve slowly in their spectral properties.

The SN rate is determined by the nuclear continuum blue luminosity. A starburst core with a continuum magnitude of $M_B = -16.3$ should have 1 SN event every 100 years. As the cSNR remains detectable against such a background for about 10 years, one in every 10 LLAGNs with $M_B \approx -16.3$ should show broad Hα emission, and 1 in every 100 should be found to have a very bright BLR corresponding to a cSNR less than a year old.

Two additional predictions for LLAGNs that stem from the properties of old cSNRs are (1) that the FWHM of the broad lines in LLAGNs should be smaller than in more luminous AGNs, and (2) that the FWHM should decrease slowly with time as FWHM $\propto V_{shock} \propto t^{-5/7}$ while its luminosity should decrease as $L_{Bol} \propto t^{-11/7}$ and the X-ray spectrum of the BLR of LLAGNs should be much softer than that of typical Seyfert type 1 nuclei. A relation between the FWHM of the broad lines and the X-ray spectrum is therefore expected in the sense that those LLAGNs with lower luminosity should have also smaller FWHM and softer X-ray spectra.

4. The Energy per Supernova

In the starburst model for AGNs, the value of the average energy per SN is *not* a free parameter but is constrained by the observed equivalent width of Balmer recombination lines, i.e., the ratio of the total flux in the line to the monochromatic flux in the underlying continuum, like Hβ ($W(\mathrm{H}\beta)$). In this model, the flux in the broad lines is proportional to the total ionizing flux emitted by the cSNR and therefore proportional to ν_{SN}, while the optical continuum is mainly due to the stars. The constancy of the $\nu_{\mathrm{SN}}/L_{\mathrm{B}}^{\star}$ described in the previous section implies that $W(\mathrm{H}\beta)$ depends only on the energy radiated per SN. The emitted Hβ luminosity of a cSNR corresponds to $\sim 3\%$ of the total luminosity (Terlevich et al. 1992). On the other hand, the underlying continuum comes mainly from the stars of the cluster with a contribution of $\sim 17\,\epsilon_{51}\%$ from the cSNR. Combining Maeder (1990) stellar evolutionary models for the stellar component with Terlevich et al. (1992) models for cSNRs, AT determined that the Hβ equivalent width in a starburst core is

$$W(\mathrm{H}\beta) \approx 40\text{Å}\,\frac{\epsilon_{51}}{1+0.17\epsilon_{51}}, \tag{3}$$

independent of the SN rate and, therefore, of the total luminosity of the AGN. Furthermore, $W(\mathrm{H}\beta)$, like $\nu_{\mathrm{SN}}/L_{\mathrm{B}}^{\star}$, is almost independent of the choice of IMF or cluster age; it is, nevertheless, weakly dependent on the adopted bolometric correction for the cSNR. The use of equation (3) to determine the value of ϵ_{51} gives a result that is independent of the adopted cosmology.

$$\epsilon_{51} \approx \left(\frac{40\text{Å}}{W(\mathrm{H}\beta)} - 0.17\right)^{-1} \tag{4}$$

Eq. (4) is of fundamental importance. It indicates that the observed narrow range of values of $W(\mathrm{H}\beta)$ in AGNs (Yee 1980; Shuder 1981; Goodrich 1989; Netzer 1990; Binette, Fosbury & Parker 1993) may be related to a universal value of the total energy per SN. This is a strong result, almost independent of the choice of either cosmology, IMF, or SN bolometric correction. Eq. (4) therefore provides a strong test of the model.

The published values for the universal $W(\mathrm{H}\beta)$ in AGN ranges from 50 Å (Shuder 1981) and 63 Å for X-ray selected AGNs (Goodrich 1989) to 100 Å in type 1 Seyferts (Goodrich 1989; Binette et al. 1993). The higher values correspond to $W(\mathrm{H}\beta)$ measured with respect to the so-called non-thermal continuum and represent an overestimate of the observed $W(\mathrm{H}\beta)$. For an average $W(\mathrm{H}\beta) \approx$ 75 Å. Eq. (4) predicts the average energy per SN to be 2.8×10^{51} ergs s^{-1}. The best modern determinations of the kinetic energy of type II SNe are 3×10^{51} ergs for SN 1979C (Branch et al. 1981) and 1.5×10^{51} ergs for SN 1987A in the LMC (Woosley 1988).

5. Rapid UV Variability and the Nature of the Lag

Terlevich et al. (1994) have analyzed the time-dependent processes that occurs prior to thin-shell formation in rapidly radiating cSNR, as maximum luminosity is achieved. They have found that an inherent delay between the photon emission and the time required to increase the density of the cooling gas leads to a lag between the observed continuum burst and the emission-line response. This delay is intrinsic to the physical processes investigated and not related to the geometry of the system; there are in fact no light-crossing time arguments involved. The final width of the cold shell is only about 10^{13} cm (about 300 light seconds), yet delays of up to several weeks between continuum and line emission maxima are generated during its formation.

Early in the evolution of the cooling wave, large photon fluxes are available but the UV/optical emission lines are very faint due to the high ionization parameter associated with the still relatively low electron density and the low column density of the cold material. As the cooling wave evolves, however, this column density soon exceeds 10^{21} cm^{-2} and its density starts to increase over the post-shock value (4×10^7 cm^{-3}). As a consequence the ionization parameter, initially > 10, begins to decrease and lines like N V $\lambda1240$ and He II $\lambda1640$ start to be emitted copiously. By the time the density of the compressed shell reaches $\sim 2\times10^9$ cm^{-3}, the ionization parameter has dropped to ~ 0.1 and the electron temperature of the ionized gas is $\sim 10^4$ K. At this time, lines like Lyα and C IV reach their maximum intensity with a delay of several days with respect to the start of the UV burst. C III] $\lambda1909$ shows a longer delay in all models. Other lines, like the Balmer series, have even longer delays, with the longest being those of Mg II and Fe II, which are longer than a month.

One lag-producing flare per cSNR is predicted, which is the longest and most energetic one. As this luminous flare is produced at the maximum of the light curve, one important prediction is that flares showing lags between continuum and emission lines are expected to occur close to the maximum of the light curve. Conversely, no further luminous and lag-producing flare is expected close to the absolute minima of the light curve.

Terlevich et al. (1994) compared the predicted shape and luminosity of the light curve of the emission lines from the cooling wave models with the observations of NGC 5548. Table 2 shows a compilation of the cross-correlation results of the UV and optical campaign of NGC 5548 (Clavel et al. 1991; Peterson et al. 1991) together with the results from the models. A quick inspection of Table 2 indicates that for *all* the observed emission lines the lags are similar to the model predictions. Furthermore, the observed and predicted peak luminosities of the emission lines for the well-sampled second pulse are remarkably similar.

After the first cooling event, dense cold gas will always be present in the outer shell immediately reprocessing the inward-moving ionizing radiation produced by further cooling instabilities; little or no lag occurs between continuum and lines as was observed in the third pulse of the NGC 5548 monitoring campaign.

Given the simplicity of the model and the small number of free parameters (basically only one, the circumstellar density), it is remarkable that the simplest cSNR model for the BLR (spherically symmetric with constant density ISM) is capable of giving a detailed and accurate description of the physical conditions

Table 2. Observed and predicted lags for NGC 5548

Line	Lag (days) Observed[a]	Lag (days) Predicted	Peak Luminosity (10^{40} ergs s^{-1}) Observed[a]	Peak Luminosity (10^{40} ergs s^{-1}) Predicted
Lyα λ1215	12	10 – 15	100.	90.
N V λ1240	4	2 – 10	30.	14.
Si IV λ1440	12 – 34	12 – 17	13.	23.
C IV λ1550	8 – 16	10 – 15	100.	280.
He II λ1640	4 – 10	12 – 20	15.	26.
C III] λ1909	26 – 32	20 – 30	18.	13.
Mg II λ2800	34 – 72	40 – 50	10.	26.
Hβ λ4861	20	30 – 40	8.	7.5

[a] Observed values are for the second flare in 1989.

and line ratios (Terlevich et al. 1992), and in addition provides a good prediction of the temporal behavior of the broad emission lines in NGC 5548. It is even more remarkable when considering that the assumed value of the circumstellar density is not actually a free parameter, but measured in true cSNRs like SN 1988Z, SN 1987F and bright radio supernovae (Filippenko 1989; Stathakis and Sadler 1991; Terlevich et al. 1994).

6. Conclusions

Several important predictions in the starburst model are relatively simple to check. As the supernova rate (or number of peaks of the light curve) is related to the blue-band stellar light (or minimum of the light curve recorded), independently of the initial mass function, age and/or total mass of the cluster, there should be a tight relationship in low-luminosity AGNs between the number of slow component peaks in the light curve (i.e., the SN rate) and the luminosity at minimum (i.e., the unperturbed cluster luminosity).

The variability amplitude observed in AGNs should reach a maximum for those nuclei with luminosities similar to the maximum luminosities of cSNRs, i.e., $M_B \approx -20$. AGNs with both higher and much lower luminosity should show less amplitude of variability due to the superposition of cSNR events in the first case, and due to the fact that we are seeing old and less luminous cSNRs with slowly evolving spectral properties in the case of LLAGNs ($M_B \gg -20$).

The FWHM of the BLR lines in LLAGNs should be smaller than in more luminous AGNs and should decrease slowly with time as FWHM $\propto t^{-5/7}$ while its luminosity should decrease as $L_{Bol} \propto t^{-11/7}$. The X-ray spectra of the BLR of LLAGNs should be softer than those of typical type 1 Seyferts. The least luminous LLAGNs should therefore also have the narrowest broad lines and softer X-ray spectra. Observations of a well-defined sample of LLAGNs should provide enough information to test the predictions of the model.

Due to the stochastic nature of the SN activity and the low SN rate in low-luminosity AGNs, transient stages of type 2 Seyferts, as observed in some broad-line LINERS and type 1 Seyfert nuclei, can naturally occur.

The time-averaged $W(\mathrm{H}\beta)$ is related to the mean energy per SN, independent of the initial mass function, age and/or total mass of the cluster, and of the assumed cosmology. The constancy of $W(\mathrm{H}\beta)$ in AGNs may be related to a near-universal value of the energy in a type II SN explosion of about 3×10^{51} ergs.

Regarding line variability, the time-dependent processes during thin-shell formation in a rapidly radiating supernova remnant can potentially produce time delays between the continuum and line emission with values similar to those observed in nearby type 1 Seyferts. The predicted delays are shorter for the high-ionization lines than for the low-ionization ones. The theory also predicts the occurrence, after shell formation, of shorter and less energetic flares with little or no lag between continuum and lines.

Obviously, much more work is needed both in further developing the theory and in verifying the predictions. An extended study of the variability of AGN over wide range of luminosities which includes LLAGNs with well-sampled light curves is clearly needed to test the consistency of the predictions of the starburst model. Important questions that remain to be explored regarding the variability of AGNs include:

- Does the observed continuum variability in radio-quiet AGNs correspond to a Poissonian process with a typical energy about 3×10^{51} ergs per event?
- Can the starburst model explain the observed rapid X-ray variability on time scales down to few hundred seconds?

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Reverberation Mappers and AGN Theorists — A Necessary Symbiosis

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Abstract. Knowledge of the gas flow in the broad emission-line regions of AGN is essential for an understanding of the fueling of their central engines. In this paper, we emphasize the physics of these regions and their relevance to reverberation-mapping studies. We first present an overview of the meeting from the perspective of AGN theorists. We then discuss the relationship of the assumptions of reverberation mapping to physical models. Finally, we discuss some of the directions for the development of reverberation-mapping programs suggested by these physical models.

1. Introduction

In 1984, Bernard Pagel, paraphrasing George Orwell, said “all galactic nuclei are active, but some are more active than others” (Pagel 1985). How true! Over the past decade it has become clear that ultra-luminous QSOs are but the tip of an iceberg of activity; not surprisingly, controversy — albeit accompanied by some consensus — surrounds current research into the nature of nuclear activity.

Astrophysical phenomena — and research — often exhibit cyclic behavior. AGN research has gone through several historical cycles: some of the earliest ideas about nuclear activity invoked the primary rôle of stars, largely through their evolution to supernovae (e.g., Shklovskii 1960; Field 1964; Colgate 1967). This was followed by a swing towards study of long-lived gravitational processes in compact regions, after it became apparent that the early stellar models had difficulties, both with energy efficiency and in explaining the occurrence of rapid continuum variability (Lynden-Bell 1969). Accretion of matter onto a supermassive black hole (BH), through the intermediacy of a disk became, and remains, the paradigm for the source of AGN luminosities. However, interest in the rôle of stars, particularly supernovae, in nuclear activity is once again current, both on their own, and in consort with supermassive black holes (see §3.1 and the review by Perry 1993). This interest has arisen partly out of the failure of black-hole-only models to account for much of the phenomenology accompanying the intense luminosity (which they were designed to explain), in particular the failure to account for the occurrence and structure of the broad-line emitting gas — which forms the subject of this conference.

Energy generation by accretion onto a black hole requires a reservoir of accretable material large enough to sustain the source over its lifetime. It appears likely, at least for low-luminosity AGN, that stellar mass loss during normal stellar evolution, and/or the general galactic interstellar medium (ISM), can provide enough mass to fuel the central engine. This view is supported by the (admittedly sparse) evidence for extranuclear fueling (Heckman 1992). (In this context, extranuclear implies a region not overly affected by the gravitational influence of the central engine.) However, the high mass-consumption rates required to explain the highest-luminosity AGN (up to hundreds and even thousands of solar masses per year) are not readily accounted for this simply.

In order to study these fueling processes observationally, it would be necessary to resolve the gas dynamics of the nuclear region. By far the most detailed information available to us to use to try to delineate the structure of nuclear gas flows is contained in the broad emission lines (BEL). It is clearly important to understand the broad-line emitting region (BELR): the region almost certainly lies in the fueling path towards the central black hole. This is a fundamental motivation of studies of the (BELR), and in this review we look at reverberation mapping — which is the attempt, in the absence of spatial resolution, to "map" the BEL gas — in this context.

Interpretation of the information carried by the BEL requires astrophysically developed gas dynamical models of the region. The observations make clear that the BELR is both structurally complex and dynamically active.

Paradoxically, a major hindrance to developing models for the BELR has been the sheer success of photoionization models for the emitting gas. These models invoke the excitation of dense ($\gtrsim 10^9\,\mathrm{cm}^{-3}$) clouds by strong ionizing continuum radiation fields. Adjustments to the thermal and ionization equilibria of the gas take place on time scales which are effectively instantaneous, and thus studies of these equilibria can be decoupled from essential problems such as the formation and survival of the clouds. As a result, the interpretation of reverberation studies from a purely photoionization perspective has led to the investigation of BELR models in which photoionized clouds are assumed to exist, *ad hoc*, divorced from issues such as their formation and hydrodynamical context. However, these issues must be addressed if the structure and dynamics of the nuclear gas, and ultimately the fueling of the central continuum source, are to be understood.

Observational data provide the ultimate test of models, regardless of the claims and counter-claims of theorists. The most powerful test of BELR models would be a space and velocity-resolved map of the emitting gas. Since this is not yet possible, reverberation studies, with all their attendant complexities, have assumed a dominant rôle. Different BELR models predict different geometrical and velocity distributions for the emitting gas, and therefore a range of transfer functions and line profiles. It is also important to emphasize that apart from the now discredited "standard" model, in which mythical long-lived clouds follow some ordered velocity pattern, all models predict some evolution of the BELR. Transfer functions and line profiles are thus expected to exhibit short and long-term temporal variations.

The most serious difficulty in effecting a reconciliation between reverberation studies and the physical models is that the former demand a particular