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QUANTITATIVE SPECTROSCOPY OF STARBURST AND QUASAR EMISSION LINE REGIONS

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RESUMEN

Los cuasares y las galaxias con brotes de formación estelar son de los objetos más lejanos que podemos observar directamente. Una vez que las entendamos, sus líneas de emisión pueden darnos información sobre la luminosidad y la composición química de la galaxia huésped. También podremos rastrear la expansión del Universo a $z \leq 5$ y los efectos de las primeras generaciones estelares. Estos serían los resultados a largo plazo de nuestro trabajo. A más corto plazo, deseamos simular el espectro de plasmas fuera de equilibrio. Describimos los pasos que están siendo tomados para incluir la base de datos atómicos requeridos para simular la emisión de líneas y las aplicaciones para obtener información del espectro de regiones de emisión.

ABSTRACT

Quasars and starburst galaxies are among the most distant objects we can directly observe. Once understood, their emission lines will measure their luminosity and the composition of the interstellar medium of the host galaxy. We will then be able to map out the first generations of stellar processing in the cores of massive galaxies, and directly chart the expansion of the Universe at redshifts $z \leq 5$. Such understanding is the long-term goal of our work. It is coupled to short-term questions, especially the ability to simulate a non-equilibrium plasma and predict its spectrum. We outline the steps now being taken to obtain the underlying atomic data base needed to simulate these emission line regions, the large-scale calculations now routinely done, which can explicitly take into account the effects on non-homogeneous emission line regions, and finally the application of these calculations to the unraveling the message held with the spectrum of these objects.

Key words: **GALAXIES: ACTIVE — GALAXIE: STARBURST — LINE: FORMATION — STARS: FORMATION**

1. INTRODUCTION

This is a progress report on our efforts to unravel the message of the emission line regions of the active galactic nuclei. Since the problems we face are largely the same, we consider quasars, Seyfert galaxies, and Starburst galaxies under the general heading of AGN. The quasars are the most luminous objects in the universe and the highest redshift objects we can directly observe. Understanding their emission lines has a cosmological imperative since their spectra depend on luminosity (Baldwin 1977; Boroson & Green 1992; Osmer et al. 1994). Once we can directly measure their luminosity, the quasars will gauge the expansion of the universe at redshifts $z \leq 5$. At the same time, the origin of the chemical elements remains a central theme across much of stellar, galactic, and extragalactic astrophysics. AGN probe early epochs in the formation of massive galaxies and their emission lines can reveal the composition of the Interstellar Medium (ISM) when the universe had an age well under a billion years.

Deducing reliable abundances and luminosities of emission line objects is the central theme of this work. Emission lines are produced by warm ($\sim 10^4$ K) gas with moderate to low density ($n \leq 10^{12}$ cm^{-3}). Such gas is far from equilibrium and its physical conditions cannot be known from analytical theory. Rather, the observed spectrum is the result of a host of microphysical processes which must be numerically simulated in detail. Towards this end we have developed the spectral synthesis code Cloudy, and applying it to understand observations of AGN.

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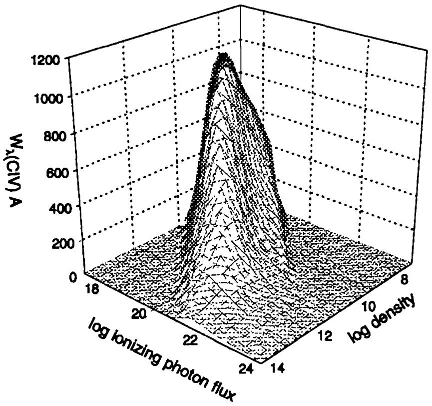

Fig. 1. C IV 1549 equivalent width for a wide range of densities and flux of photons.

2. CLOUDY

The ionization, level populations, and electron temperature are determined as a function of depth by self-consistently solving the equations of statistical and thermal equilibrium. Lines and continua are optically thick and their transport must be treated in detail. Predictions of the intensities of thousands of lines and the column densities of all constituents result from the specification of only the incident continuum, gas density, and its composition. By their nature, such calculations involve enormous quantities of atomic/molecular data describing a host of microphysical processes, and the codes involved are at the forefront of modern computational astrophysics. Although the task is difficult, the rewards are great, since numerical simulations make it possible to interpret the spectrum of non-equilibrium gas on a physical basis.

Cloudy's source (about 110000 lines of Fortran) and its documentation Hazy. a Brief Introduction to Cloudy (UK Physics Internal Report, 461 pages) are freely available on the World Wide Web (http://www.pa.uky.edu/ gary/cloudy). This web page also has Dima Verner's Atomic Data for Astrophysics (ADfA) web page (http://www.pa.uky.edu/ verner). This provides independent public access to the numerical forms of the atomic data used by Cloudy.

3. AGN AND STARBURST EMISSION LINE REGIONS

The line spectra of all AGN are challenging because of the plasma and atomic physics issues affecting any numerical simulation, compounded by the fact that the emission line region is unresolved. reflection must play a role (certainly in the X-Rays; Nandra 1994), the continuum possibly beamed and so depends on geometry, and both the continuum shape and the gas metallicity may scale with luminosity. If we can answer these questions, we will understand the AGN. These are all difficult problems. but I believe that we are close to having the computational tools needed, and that rapid progress is now possible.

3.1. The LOC Approach

The "Locally Optimally-emitting Clouds" (LOC) model is outlined in Baldwin et al. (1995). Figure 1 shows an example, the predicted C IV 1549 equivalent width, as a function of cloud density and flux at the illuminated face (equivalent to radius). Clearly a powerful selection effect is at work. The line is efficiently produced over only a narrow range of conditions —very similar to those thought to be "standard parameters". Figure 2 shows predicted equivalent widths of several lines for essentially all possible cloud densities and fluxes. Different emission lines radiate preferentially at different locations in the flux - density plane. The homogeneity of AGN spectra was long a mystery (Baldwin & Netzer 1978). Baldwin et al. showed that the average quasar spectrum can be produced by simply integrating over all possible clouds. Selection effects due to the line visibility function ensure that most quasars will have very similar spectra even if their distributions of cloud properties are different.

The new aspect of our approach is allowing a range of cloud properties at a given radius, including ranges in column density and gas density. This seems much more realistic than just single-valued functions. Clouds of different gas densities could exist side-by side for several viable confinement mechanisms (magnetically or shock confined, or dissipating clouds).

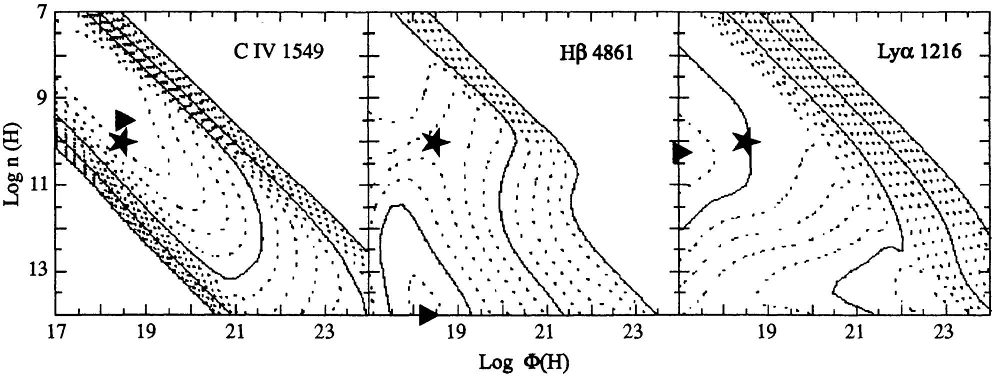

Fig. 2. Equivalent widths versus gas densities, and flux of ionizing photons. Heavy lines are 1 dex increases in equivalent width, beginning at 1. The star indicates the standard parameters of 15 years ago and the triangle is the peak line visibility.

These integrations have been carried out over the most extreme bounds; the full range of possible parameters. The line visibility functions are so strongly peaked that a typical spectrum can be easily matched. This is not an entirely positive conclusion; we want to be able to deduce conditions in the quasar from the observations. The advantage is that there is no longer any hidden hand needed to adjust cloud parameters —we are dealing with a known, calculable set of line visibility functions, which introduce powerful selection effects. An integration over the full LOC plane produces results which are in good agreement with "typical" spectra of quasars (Baldwin et al 1995). There is a large dispersion from object to object about this mean, which, together with detailed line profile studies (Baldwin et al. 1996a), suggests that this plane is not necessarily fully populated in a given object. A goal is to determine observational limits to the cloud distribution functions.

3.2. Luminosity, Continuum Shape, and Metallicity Correlations

The long-term emphasis is to use luminous quasars and starburst galaxies to probe the high redshift universe. We are continuing to develop the LOC models in order to address the following major problems concerning the BLR. There are luminosity correlations such as those in Baldwin, Wampler, & Gaskell (1989), and Osmer et al. (1994). These must be understood on a physical basis. Luminosity-line correlations are complicated by other correlations. Those include luminosity with continuum shape, most obviously $\alpha_{o,x}$ (Avni & Tananbaum 1986; Worral et al. 1987; however, LaFranca et al. 1995 find no dependence, and Avni, Worrall & Morgan 1995 find a complicated dependence). The N V/C IV relation discussed by Hamann & Ferland 1992, 1993) suggests a metallicity - luminosity correlation (Baldwin et al. 1996a; Ferland et al. 1996). These are all fundamental to understanding the messages of the lines.

3.3. The Narrow Line Region

We (Ferguson et al. 1996) are extending the LOC grids to compute the emission expected from a dusty environment as might be produced by the illuminated face of a molecular cloud, a natural source for starburst narrow line region (NLR) gas. Calculations assuming Orion abundances and grain populations (Baldwin et al. 1991) are shown in Figure 3. The two [O III] lines shown, 4363 and 5007, are the main optical nebular temperature indicators (Osterbrock 1989). The 5007/4363 ratio has long been known to be inconsistent with a single photoionized cloud and that line widths correlate with critical density (Filippenko & Halpern 1984; Ho, Filippenko, & Sargent 1996.) Clearly line emission comes from a mix of clouds with very different properties.

Figure 3 shows that the peak visibility of the two lines is different due to different atomic physics; 4363 forms at smaller radii and higher densities. The integrated intensity and profiles are predict by integrating over the distribution, with the added assumption that the cloud motion is gravitational with a potential well. The predicted 5007/4363 ratio is much smaller than photoionization of a single cloud would indicate, in agreement with observations. Figure 4*b* shows predicted widths correlated with critical density, with the mean predicted slope as a line and specific emission lines as points. The agreement with observations is excellent. We are working on the interface between the dusty gas modeled in Figure 3 and the grain free gas found at smaller radii. Grains are destroyed when their temperature rise above the sublimation point (Sanders et al. 1989), and they

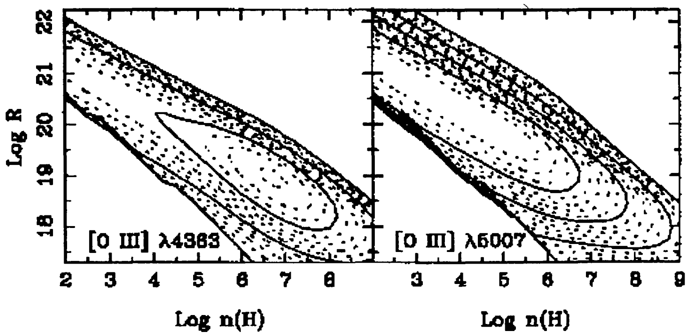

Fig. 3. Predicted [O III] 4363 and 5007 equivalent width as a function of the cloud density and the distance from the AGN nucleus. Heavy lines are 1 dex increases in equivalent width, starting at 1.

must be removed from the calculation and the gas-phase abundances of refractory elements restored. We save the continuum emitted by each cloud, and predict the IR spectrum of the ensemble. Determining abundances in NLR gas is another goal.

We will also be extending the simulations to include the effects of the radiatively driven flow away from the postulated H II region - PDR interface. Dusty gas has an opacity many orders of magnitude larger than electron scattering, so the effective Eddington limit is much smaller. Winds are driven from the face of the molecular cloud resulting in outward motions amounting to many hundreds of km s^{-1} for some conditions. This outward motion, together with a central source of obscuration, could produce the types of NLR asymmetries observed by Whittle (1992).

3.4. Fe II Emission in AGN

The message of Fe II emission has never been fully exploited, in part because only recently have collision strengths, transition probabilities, and a complete set of energy levels, become available. The dispersion in Fe II intensities from object to object is among the greatest shown by AGN lines - Fe II is clearly trying to tell us something. We are incorporating a large Fe II atom into Cloudy (Baldwin et al. 1996). The effects of the Fe II atom on heating/cooling, and the interaction of the atom with its environment (by continuum pumping, line overlap, destruction by background opacities) are all included. Over 10^4 emission Fe II lines are predicted, and the lower portion of Figure 4b shows the Fe II emission alone. Our goals here are two fold, to include the thermal effects on the cloud (this is major, since Fe II line can be so strong), and to develop indicators needed to use Fe II to probe conditions. For instance, the Fe II spectrum has strong density dependencies. Our current work centers on completing the Fe II model atom, incorporating the latest Iron Project collision data, identifying missing energy levels and selective excitation processes. We are also comparing our predictions with the Boroson Fe II template, the QSO I Zw I, and RR Tel as an essential steps in confirming the fidelity of the simulations.

Our eventual goal is to be able to say something quantitative about Fe abundances in high redshift objects, and determine what physics makes an AGN FeII loud or quite. The eventual goal is to quantitatively identify the time when the universe passed through a billion years by detecting the order of magnitude increase in iron abundance due to Type 1 supernovae (Hamann & Ferland 1993, Fig. 1; see also Elston, Thompson, & Hill 1994). This is the time set by the lifetime of the highest mass star which leaves behind a white dwarf).

4. CONCLUSIONS

We have outlined our work on understanding the emission line regions of Active Galaxies, including Starburst Galaxies. It is no overstatement to say that are at a watershed in quantitative astronomical spectroscopy. The grids of calculations described above, which led to the realization that powerful selection effects alone can explain the spectrum of a typical quasar, were simply impossible a decade ago - the computational power was not available. This power has also resulted in spectacular advances in the basic atomic data base, since the vast majority of the millions of pieces of atomic data used in our simulations are the result of large-scale ab initio quantal calculations. Dima Verner's ADfA page would not have been possible ten years ago. At the same time, a revolution in the observations is taking place with new telescopes making

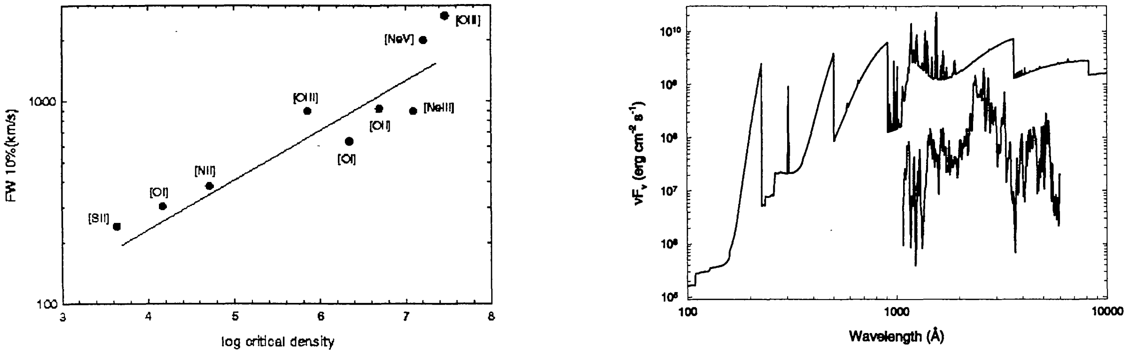

Fig. 4. *a)* Line width-critical density correlation for the NLR LOC calculations. Points indicate predicted widths for individual lines, and the line is a fit to the points. *b)* Emission from a BLR cloud. The upper curve is the total emission and the lower is the Fe II emission alone.

quantitative observations of faint objects possible, and new spectral regimes (especially spectroscopy in the IR) opening to quantitative analysis for the first time.

The goal of using the emission line regions of active galaxies to probe the first generations of star formation and measure the luminosity of the most distant objects, has always been the object of AGN emission line research. Although the goal was identified long ago, the tools needed to do this did not exist. They are present today. The next few years will witness extraordinary advances in our understanding of AGN.

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