Quasars are the most luminous objects in the universe and the highest redshift objects we can observe spectroscopically. Understanding their emission lines has a cosmological imperative since their spectra depend on luminosity. Once we can directly measure their luminosity the quasars will gauge the expansion of the universe at redshifts z < 5. At the same time, the origin of the chemical elements remains a central theme across much of stellar, galactic, and extragalactic astrophysics. Quasars 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 galactic and extragalactic emission line objects is the central theme of this proposal. These lines are produced by warm (~10^4 K) gas with moderate to low density (n < 10^{12} cm^{-3}). Such gas is far from thermodynamic equilibrium and its physical conditions cannot be known from analytical theory. Rather, the observed spectrum is the result of a host of microphysical processes that must be numerically simulated in detail.

This grant supported the development of Cloudy, a large-scale code designed to simulate non-equilibrium plasmas and predict their spectra. My goals are to apply it to studies of emission line objects, but others have used it to study absorption line regions as well. 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. I have developed Cloudy as an aid to this interpretation, much as an observer might build a spectrometer.

1.1. Extensions to the simulations

The code has been extended to include ~10^4 resonance lines from the 495 possible stages of ionization of the lightest 30 elements, an extension that required several steps. The charge transfer data base was expanded to complete the needed reactions between hydrogen and the first 4 ions and fit all reactions with a common approximation. Radiative recombination rate coefficients were derived for recombination from all closed shells, where this process should dominate. Analytical fits to Opacity Project (OP) and other recent photoionization cross sections were produced. Finally, rescaled OP oscillator strengths were used to compile a complete set of data for 5971 resonance lines.
Figure 1 shows a partial indicator of the scope of this activity, the number of lines of executable Fortran, as a function of time.

1.1.1. Community use Cloudy is widely used by others in their analysis and theory of spectroscopic observations. Figure 2 shows the number of refereed papers acknowledging the use of Cloudy through 1995. At least 138 papers were published in 1993–1995, on subjects ranging from the intergalactic medium to inner regions of quasars. Although I was not a co-author on these projects, the code did play some role in their execution.

1.2. Active Galactic Nuclei

1.2.1. Narrow-lined objects Narrow emission lines of AGN form well away from the central engine, and their study can reveal much about the galactic environment. We examined the conditions within a cooling flow filament exposed to the radiation field of its environment, and followed the conversion of the grain-free gas from fully ionized to a fully molecular state. Ref 14 simulated conditions in gas near the center of the Milky Way, and predicted our optical emission line spectrum by matching the IR lines. Our galaxy would be classified as an HII galaxy by observers at the Virgo cluster. We showed that very high excitation lines detected by the Hopkins Ultraviolet Telescope (HUT) in NGC 1068 did not require very high (shock-like) temperatures. A photoionized gas produces these lines by a combination of continuum pumping and dielectronic recombination, and fits the NGC 1068 observations quite well.

1.2.2. Geometry of the broad line region The old picture of the broad line region (BLR) was a set of clouds with a homogeneous column density and ionization parameter (a picture shown to be incorrect by reverberation mapping). We showed that a population of low column density, optically thin, clouds must be present to explain the types of variability. We detected Ne VIII 774 and showed that this required a new population of very high ionization clouds. Distributed emission is further suggested by the delayed responses to continuum variability. The result of these studies is a picture of clouds with a very broad range of distances from the continuum source, densities, and levels of ionization.

We analyzed high resolution line profiles of high luminosity and high redshift quasars. Lower ionization lines such as Al III] and Mg II...
form at high density, and were much sharper than high ionization lines such as NV. Radiative acceleration driving the $10^4$ lines in Cloudy could push a wind from main sequence stars and produce the observed gas. This work was synthesized in the “locally optimally-emitting clouds” (LOC) model in which the line emitting environment has a wide range of properties but a uniform spectrum because of selection effects. The model will be developed to predict line variability, profiles, and intensities.

1.2.3. Metallicities in quasars This has been a major emphasis. These papers established that the NV/CIV ratio increases with luminosity, which we interpreted as a metallicity - luminosity relation. We carried out extensive calculations to reproduce observed limits to NV/CIV and NV/HeII in high luminosity high redshift quasars. Gas in the most luminous quasars had metallicities of at least 5 times solar. These metallicities are similar to those present in the ISM of massive galaxies during early epochs of rapid star formation. We examined implications of spectroscopy of broad absorption line gas and concluded that the absorbing gas has an enrichment consistent with the emitting gas, about 5-10 times solar.

1.3. Publications Supported by NAGW-3315

1.3.1. Refereed publications


1.3.2. Internal Reports

1.3.3. Invited Reviews


1.3.4. Contributed Abstracts


