CALCIUM INFRARED TRIPLET EMISSION IN AGN

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ABSTRACT. Emission in the Ca II infrared triplet lines has been detected in 15 AGN. Correlations with optical Fe II emission and O I λ8446 linewidths indicate that Ca II emission comes from neutral gas within the BLR. A new series of ionization models that extend to column densities N_H of 10^{25} cm^{-2} match the Ca II line strengths and various line ratios. The solution to the Ca II problem, which also solves the "Fe II problem" and the "energy puzzle", is that a small amount of H^- dominates the heating, even for $N_H \sim 10^{22}$ cm^{-2}, by absorbing the powerful near-infrared (1 μm) continuum.

We discuss the results of a new series of ionization model calculations for the BLR, aimed at studying the production of the calcium infrared triplet at 8498, 8542 and 8662 Å (henceforth X,Y,Z). This diagnostic, a simple alternative to Fe II, probes high density and extremely high column density neutral gas strongly shielded from the incident ionizing continuum. A suggested answer to the "Fe II problem" is that a cool, *non-radiatively* heated zone is required; this solution can be tested as well by examining the ionization and heating requirements of Ca^+.

We use the Ca II data of Persson (1988), together with published and unpublished spectra and energy distributions to assemble a list of properties that a successful model should reproduce: (1) XYZ/H$\beta \sim 0.2$ (XYZ is the sum of the line strengths); (2) X=Y=Z: the transitions are very optically thick; (3) Ca II H and K are not seen in AGN (except for I Zw 1)— typically Ca K/XYZ < 0.20 (3σ upper limit including reddening); (4) The [Ca II] lines at $\lambda\lambda$7291, 7324 (henceforth F1 and F2) are not seen—typically F1+F2/XYZ < 0.15 (3σ).

A "standard" BLR model (see Davidson and Netzer 1979) was calculated with the photoionization code described by Ferland and Rees (1988). Small plane parallel BLR clouds have a constant density of $10^9 - 10^{10}$ cm^{-3}, (chosen to reproduce the observed C III] λ1909/C IV λ1549 intensity ratio). Column densities are assumed to be $\sim 10^{23}$ cm^{-2}, and the ionization parameter U= 10^{-2}. The ionizing continuum is that given by Mathews and Ferland (1987), and calcium has a solar abundance.

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The results of this series of models are first that the F1+F2/XYZ upper limits require a density of $N_H > 10^{9.7}$ cm^{-3}, consistent with the standard value. There are two major problems. First, XYZ/Hβ is 0.008 compared to the observed 0.20. Second H+K/XYZ is predicted to be $\sim 1 - 10$, which is much larger than the observed upper limits. (The latter result is independent of abundance uncertainties.) An obvious solution is that the resonance H and K lines are destroyed on dust in the BLR gas, but this leads to problems analogous to those encountered in trying to invoke dust destruction of Lyα.

The basic requirement to reproduce the observed Ca II spectrum is to deposit large amounts of heat at very large optical depths. In this case the optical depth in the K and H lines will be large enough for the lines to be thermalized, while the infrared triplet will continue to be produced. This requirement is closely related to the "energy budget" problem of Netzer (1985) and Collin-Souffrin (1986): the amount of heat deposited in a BLR cloud, per hydrogen ionization, is much larger than expected from the observed ionizing continuum. Therefore, a series of calculations was done in which the column density of a cloud with a constant hydrogen density of 10^{10} cm^{-3} is increased above the canonical value of 10^{23} cm^{-2} up to 10^{25} cm^{-2}. A key ingredient in the calculation is the inclusion of H^- heating. Although only a trace amount of hydrogen is in the form of H^-, the opacity provided by this ion is large and in fact couples the (large) continuum infrared luminosity to BLR gas for $N_H > 10^{22}$ cm^{-2}.

The effect of increasing the column density is, as expected, to strengthen lines from ions with low ionization potentials. The model successfully reproduces the calcium spectrum, with H and K becoming thermalized at column densities greater than 10^{24} cm^{-2}. XYZ/Hβ = 0.2 at $N_H = 10^{24.6}$ cm^{-2}, where H+K/XYZ = 0.3 and Lyα/Hα = 4. XYZ/Hα is extremely sensitive to the location of the carbon ionization front, and increases by a factor of twenty between models with $N_H = 10^{24.5}$ and 10^{25} cm^{-2}. This explains why calcium triplet emission is not more common in AGN.

In conclusion we have found a good possibility for a solution to the "energy puzzle" and Fe II problem of the BLR. It is that the deeply shielded regions contain enough H^- ions to provide a significant opacity to the powerful near-infrared continuum around 1 μm. This energy input may be sufficient to power the low ionization region without non-radiative heating in an accretion disk.

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DISCUSSION

KALLMAN What happens to your models at column densities greater than 10^{24} cm^{-2}? Does the growth of the Ca II IR lines continue, or is it limited by depletion of IR continuum or by molecule formation?

PERSSON The models stop at column densities of $10^{25.5}$ cm^{-2} In the models run so far, molecule formation is not included and photoionization of H^- dominates the heating. All three Ca II lines will eventually thermalize because the optical depths in them become very large, but they are continuing to increase between 10^{24} and $10^{25.5}$ cm^{-2}.