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**Investigating the Mechanisms Responsible for Anomalously High Electron Temperature in Narrow-Line AGN**

**Introduction**

Nebular clouds in star forming regions and active galactic nuclei (AGN) typically show electron temperatures around *Te* = 1.5x104 K in the OIII emitting region (Osterbrock & Ferland 2006). However, anomalously high values *Te* > 1.54x104 K have been noticed in surveys for decades without a thorough explanation for the physical mechanism responsible for creating such conditions in narrow line emitting AGN (Shuder & Osterbrock, 1981, Komossa & Schulz 1997, Zhang et al., 2013, Richardson et al., 2014). While more recent work has started to address the topic head on, signatures of high *Te* have been present in small spectroscopic samples of AGN.

Shuder & Osterbrock (1981) showed *Te* > 1.7x104 K in 5 of the 12 galaxies for which they measure electron temperature, but do not include any models in their work, which left the question of why such high *Te* is observed in some galaxies. Komossa & Schulz (1997) investigated a larger data set, including 37 galaxies in their study. They also include models in their analysis, which includes assuming various properties of the cloud to predict emission lines, through which they can predict conditions within the cloud. Values are assumed for the spectral energy distribution (SED) (e.g accretion disk blackbody temperature) and a luminosity of hydrogen ionizing photons emitted by the galactic nucleus. Along with cloud distance from the emission source and hydrogen density (nH), these values can be used to calculate the ionization parameter *U*. The wide range of parameters varied led to a range of log *U* between -6.58 and +0.42. Komossa & Schulz (1997) also varied the metallicity of the cloud, *Z*, and stop their models once the hydrogen column density dropped below a pre-determined value. These input parameters were used in a photoionization code called Cloudy c84.03 (Ferland 1993). Cloudy then outputs emission line strengths for any requested lines, and these line strengths are used to determine conditions within the cloud. This approach proves to be common when modeling the NLR. [NEED TO MENTION SOMETHING ABOUT THE CONNECTION TO HIGH TE HERE]

Dopita & Sutherland (1995) also model high temperature galaxies, but they employ shocks as an excitation mechanism to reach those high temperatures and solve the temperature problem for a small subset of objects. To model these shocks, they varied magnetic field strength from 2 < B/n1/2 < 4 μG, and shock velocity from 150 – 500 kms-1. They derive interesting results from their models, including an inverse relationship between shock velocity and electron temperature. Figure 2c shows shock models with a velocity < 500 km s -1 and without a precursor have log [O I] λ6300/Hα > -1.0, and a range of log[O III] λ5007/Hβ between 0.25 and -0.25, meaning though these lower velocity shocks produce high electron temperature (high enough to reach out hottest data points, but what’s the actual Te?), these models fall inside the LINER category on diagnostic diagrams. This result is not surprising, because as we have mentioned, LINERs are shocked AGN.

* 5007/4959 = 3/1 so use this to calculate electron temperature from the plots
* Assume a density of 10^3 and based off those ratios, these give you XXX electron temperature etc. cite O&F

Though this shock heating provides high electron temperatures, nearly all of these shock heated galaxies led to a LINER (low ionization narrow emission line regions) classification due to strong neutral line emission. Many LINERs are thought to be shock heated AGN, but these results do not provide an explanation for the high temperature photoionized AGN classified as Seyferts. In order develop a complete solution, the temperature problem also requires a solution for photoionized AGN, so this group’s results leave the question partially unanswered.

Groves, Dopita & Sutherland (2004) incorporated dust in their models in an attempt to increase electron temperature due to photoelectric heating, which at the time was a new approach. This group also used the MAPPINGS III code instead of CLOUDY to do their models. Notably, they included a narrower range of parameters than Dopita & Sutherland (1995) by varying nH from 102 – 104 cm-3, 0.25 Z☉ < Z☉ < 4.0 Z☉, and power law index α from -1.2 to -2.0 for the SED. The ionization parameter *U* was varied from -4.0 < log *U* < 0.0 in intervals of -0.3, -0.6, and -1.0 dex, and they varied grain content proportional to metallicity, though they claimed this is a gross over simplification and cannot be justified, but it is the simplest way to model the grain content. Their models showed higher electron temperatures with higher grain content, and they mentioned that including grains in their models helped alleviate some of the temperature problem, though more work is needed.

Richardson et al. (2014) investigated the effects of density, ionization, grains and metallicity on AGN gas, and referred to many of the studies mentioned above. They mentioned that Komossa & Schulz (1997) drastically overestimates [O I] emission with high density values, which likely means that high density regions do not exist. Instead, increasing density increases [O I] emission but does not affect Hα or Hβ emission, so different emission line ratios are observed. They also touched on the cooling effect of metals in the gas, explaining that increased metallicity can cool the gas and decrease electron temperatures. However, it may be the case that AGN with low metallicity values are rare, meaning that may not be a sufficient explanation for the high electron temperatures seen in some samples. Grains were shown to increase electron temperatures through photoelectric heating and can reproduce high ionization AGN Te but miss the mark with the highest ionization AGN in the sample. Interestingly, they also included a model with cosmic rays, which would provide another excitation mechanism on top of photoionization, but their model shows negligible effects on Te.

Also notable is this group’s approach to modeling. They used a local optimally emitting cloud (LOC) model, which treats the NLR as a sum of many individual gas clouds distributed around the central source. Individual clouds were modeled using Cloudy c10.0. These models were stopped once Te exceeded 100,000K or fell below 4000K, as temperatures above that range contribute primarily to X-Ray emission and temperatures any lower contribute primarily to IR emission. They then integrated over radial distance and density distributions to account for the NLR as a whole. This approach is certainly different from the models from the previously mentioned groups, but still does not provide a solution to the temperature problem. However, this approach can account for the fact that we observe the sum of all sections of the NLR and simulating this as numerous individual clouds can more accurately represent that. For example, if we observe high electron temperature and low metallicity from an NLR, it is likely that the entire NLR is not homogenously high temperature and low metallicity, but there could be pockets of low temperature and high metallicity, and this method can simulate that variation.

Zhang Liang and Hammer (2013) mentioned that the temperature problem is still unsolved. They explained though shock models have been investigated, but it is generally believed that photoionization is the dominant excitation mechanism in most AGN. In addition, shock models require shocks that permeate throughout the NLR, but this proves inconsistent because shock signatures are often not observed. Indeed, the most successful shock models (Dopita & Sutherland 1997) show LINER-like emission line ratios rather than emission line ratio typical for AGN.

They also explained that previous observations have shown that NLR clouds are likely to be dusty in nature, supporting the evidence for higher grain content in these clouds. Their most successful models were dusty, radiation-pressure dominated photoionized AGN models that included *n*H = 100 cm -3 and a power law index of -1.4. In addition, they included a discussion of the effects of low metallicity, including decreased metallicity increasing electron temperatures and decreasing the number of available high-energy photons to ionize hydrogen. Most importantly, they concluded that “some strong [OIII] λ4363 emission Seyfert 2 galaxies with Te >15000 K can be fitted with dusty AGN model grids at low metallicity (i.e. Z/ZO ~ 1.0).” This conclusion shows the combination of dust and low metallicity is capable of producing strong [OIII] λ4363 emission in AGN.

Using these previous studies, we can determine a new approach to solving the temperature problem. For our investigation, we will use a sample of galaxies taken from the Sloan Digital Sky Survey (SDSS), and filter through this data using a SQL query. We use high S/N ratios for the essential emission lines. We do not include any LINERs in our data set because we are focusing on high temperature photoionized AGN, which also means we do not investigate shocks as a possible excitation mechanism. We separate galaxies by type so we can focus on AGN. Using [OIII] λ4363, we categorize our galaxies by temperature so we can focus on the high electron temperature outliers in the data set.

We use this background data set to compare to our models, which are done in CLOUDY13.03. This newer edition of CLOUDY compared to the previously mentioned studies contains more advanced code and has updated atomic data, making our models more accurate and detailed. Our overall approach to the models is similar to that of Dopita & Sutherland (1995). We will assume certain characteristics of the cloud, including *n*H, *U*, and *Z*. However, our model will also vary grain content to explore the impact on electron temperature via photoelectric heating. Another unique aspect of our study is that it will focus on a robust exploration of the temperature problem in photoionized AGN. Numerous studies have touched on the fact that this problem exists and given attempts at solving it, but our study is unique in that it will focus specifically on the temperature problem with the sole goal of finding a solution.

[[[Turbulence shows interesting results because it gives high Te, but puts the grids in the LINER category. This could be a result of turbulence being present in some clouds of an AGN NLR and causing high [OIII]4363 observations and LINER characteristics, though the turbulence doesn’t permeate through the entire NLR.]]]] Should this go in discussion/future work? [BETTER TO PUT THIS IN FUTURE WORK]

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EVERYTHING BELOW THIS LINE IS METHODS]

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Our research focuses on this temperature problem in narrow line region (NLR) emitting Active Galactic Nuclei (AGN) [move farther down]

Our research uses data from the Sloan Digital Sky Survey as well as constraints on galaxy types established in Kewley et al. to separate our data set by galaxy type. Interestingly, our data set contains no LINERs. Shock-wave heating is a possible heating mechanism, but LINERs are shocked AGN, so because we have no LINERs, we do not explore shocks.

We plot our SDSS data set on a collection of diagnostic diagrams in order to categorize them by characteristic conditions and type. The most popular and useful of these is the BPT Diagram, presented by Baldwin, Phillips and Terlevich in 1981. The BPT Diagram is a log[OIII] λ5007/Hβ vs. log[NII] λ6584/Hα plot that conveniently separates AGN from Star Forming (SF) galaxies, composites, and ambiguous objects, all of which are contained in our data set. log[OIII] λ5007/Hβ is a hydrogen density and ionization sensitive line ratio, and log[NII] λ6584/Hα is primarily sensitive to ionization. We used this log[NII] λ6584/Hα ratio again when we separate our galaxies by temperature, in a log[OIII] λ5007/4363 vs. log[NII] λ6584/Hα plot. This neatly categorizes our galaxies by their temperature, as 5007/4363 is a temperature sensitive emission line ratio. The high temperature outliers in our data set are apparent in this temperature plot, and we use it to compare with our simulations and check the temperature of our simulations. By comparing different iterations of simulations with these plots of our data set we are able to see the effects of changing different parameters, which helps us decide how to adjust our simulations. These plots also ensure that we are using realistic values of our parameters, and likely observed conditions, by showing us whether our simulations match our data.

ZLH find the high Te Seyfert 2 show low metallicity Fig 7

LINERs and composites show Te “far too high to be explained by only stellar photoionization”

Some strong [O III] λ4363 emission Seyfert 2 galaxies with Te > 15 000 K can be fitted with dusty AGN model grids at low metallicity (i.e. Z/Z ∼ 1).

**References**

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