**Investigating the Mechanisms Responsible for Anomalously High Electron**

**Temperature in Narrow-Line AGN**

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**1. 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] (Should I just mention that Shuder & Osterbrock see anomalously high Te in 1981 and then that this modeling approach is common? Or should I be mentioning more 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. They use a diagnostic diagram that shows log[O III] λ5007/Hβ vs. log [O I] λ6300/Hα, which is particularly sensitive to shock excitation (Kewley 2006). This plot neatly separates star-forming, AGN and LINER galaxies and overlaying their shock models on this diagram reveals relevant information. Though the lower velocity shocks produce high electron temperature, in fact up to 6.5x104K, these models fall inside the LINER category. 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.

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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).

**3. Modeling the Narrow Line Region**

**3.1 The Central Source**

We conduct our modeling with CLOUDY version 13.03 (citation). We take cosmic ray background values from previous literature (Indriolo et al. 2007), (Is this the right citation?), and set gas abundances according to Grevasse et al. 2010. We set the AGN temperature, which is the blackbody temperature of the central accretion disk, to be 2x105 K, and we take spectral energy distribution (SED) values of αox = -1.42, αuv = -0.57, and αx = -1.63 from (Greene citation GET FROM ANOTHER PAPER?). We vary the ionization parameter, which is the ratio of hydrogen-ionizing photon density to total hydrogen density. (right?)

* How should I introduce this equation?

fν= ναuv exp(−hν/kTBB)exp(−kTIR/hν) +aναx

**3.2 The Cloud**

Many of our models involving varying values of metallicity, from 0.5 to 2 times solar. [VALUES? SECONDARY NUCLEOSYNTHESIS?]

* What do I need to include about secondary nucleosynthesis?

We use the metals deplete command that uses results from Jenkins 1987 and Cowie & Songaila 1986 [THIS IMPLIES THE METALS DEPLETE CHANGES METALLICITY].

* What exactly does metals deplete do? Not really getting it from hazy

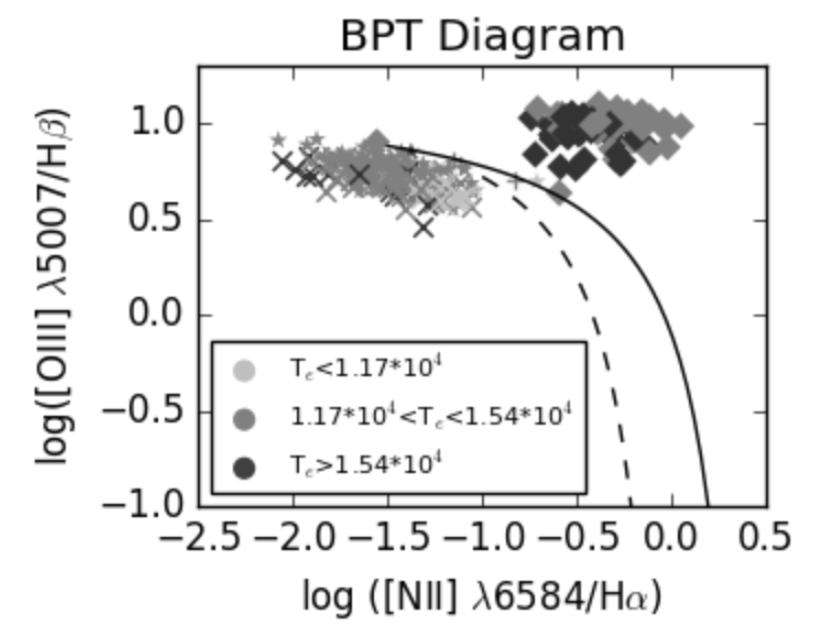
We also must manually determine the value for helium and nitrogen when we change our metallicity because they do not scale linearly with other elements (Baldwin 1991).

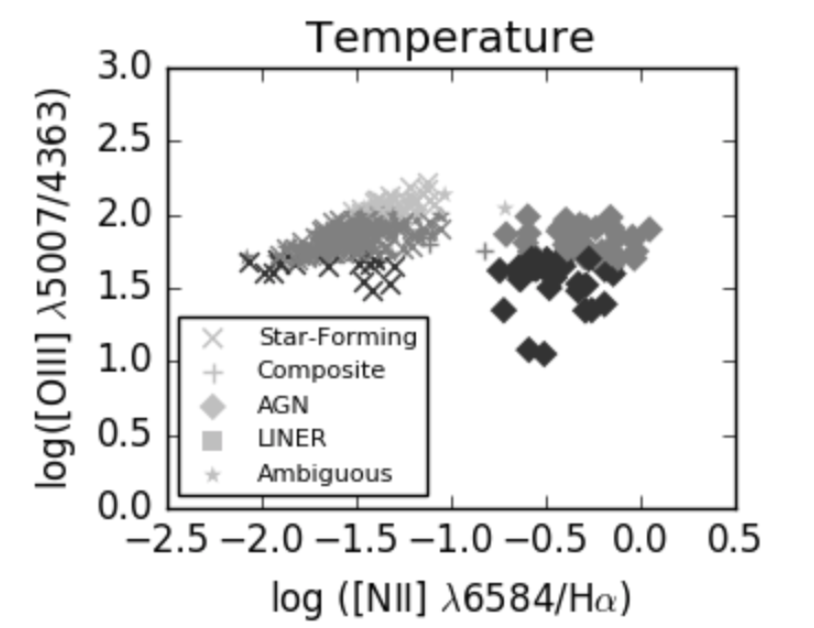
* Does this need an explanation? About hydrogen getting converted to helium etc. Also couldn’t find Hamann & Ferland 2002

We maintain constant pressure throughout the cloud, and stop our model when ne/nh = 0.01. Stopping our models at a designated density fraction allows this stopping condition to scale to all clouds and helps us accurately model OI emission, as opposed to a set depth that would remain constant for clouds of all sizes.

**3.3 Diagnostics**

To evaluate our models, we use diagnostic diagrams to plot them on top of the observation data mentioned previously. We use numerous plots to analyze our models, but one of the most important is the BPT Diagram, named after Baldwin, Phillips and Terelvich who first presented the diagram in 1981. The BPT Diagram is a plot of log[OIII]5007/Hβ vs. log[NII]6584/Hα. The diagram separates star forming galaxies, AGN and composites, which helps us know what kinds of galaxies are in our data set. To further confirm, we use calculations from Kewley et al. 2006 that allow us to shape code our data based on galaxy type. From these criteria we see that our data set contains no LINERs, which is consistent with what our BPT Diagram shows us. Using a relation between OIII λ4363, OIII λ5007 and OIII λ4959, coupled with electron densities, we can derive *Te* from a given spectrum (Osterbrock and Ferland 2006). Using this method, we color code our data based on *Te* which neatly separates our data on a plot of log[OIII]5007/4363 vs. log[NII]6584/Hα. Overlaying our models on top of each of these diagrams allows us to determine whether our models are accurately reproducing the physical conditions present in our data set.





Still need to format these correctly ^

-Defining an AGN temp and SED values taken from Christopher’s research?

-AGN T = 5.3, a(ox) = -1.42, a(uv) = -0.57, a(x) = -1.63

Set ionization parameter to -1.5

Hydrogen density ~ electron density = 2.4 10^3 cm^-3

Using abundances GASS10 (Grevasse et al. 2010)

Cosmic ray background (Indriolo et al. 2007)

Metals deplete (Jenkins 1987, Cowie and Songaila 1986)

Scale metallicity to multiples of solar values, which includes individually scaling nitrogen and helium, using a prewritten python script to scale helium

Maintaining constant pressure

Stopping when electron density drops to 1% of original value

-introduce BPT diagram and show data no sims with color and shape code and show we have no liners with the shape

-and then showing grids, export as pngs and go for 3x2

[[[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]

**References**

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