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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* = 1.5E4K in the OIII emitting region (Osterbrock & Ferland 2006).

However, anomalously high values *Te* > 1.54x104 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) show Te > 1.7E4 K in 5 of the 12 galaxies for which they measure electron temperature, but do not include any models in their work, which leaves 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), the blackbody temperature for the background emission source, and a luminosity rate 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 leads to a range of log U between -6.58 and +0.42. Komossa & Schulz also vary the metallicity of the cloud, and stop their models once the hydrogen column density drops below a pre-determined value. These input parameters were used in a photoionization code called Cloudy, specifically version 84.03 (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.

Dopita & Sutherland(1995) also model high temperature galaxies, but they employ shocks to reach those high temperatures, and claim in their abstract that they have solved the temperature problem. To model these shocks, they vary 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[OI]6300/Hα > -1.0, and a range of log[OIII]5007/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
* Plug in Te values and solve for the left side

Though this shock heating provides high electron temperatures, nearly all of these shock heated galaxies are LINERs, or low ionization narrow emission line regions. LINERs are shock heated AGN, but these results do not provide an explanation for the high temperature photoionized AGN. The temperature problem requires a solution for photoionzed AGN, so this group’s results leave the question unanswered.

Groves, Dopita & Sutherland (2004) incorporate 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 uses the MAPPINGS III code instead of CLOUDY to do their models. Notably, they include a narrower range of parameters than Dopita & Sutherland in 1995. They vary nH from 102 – 104 cm-3, metallicity from 0.25 – 4 times the solar value, and power law index α from -1.2 to -2.0. The ionization parameter U is varied from -4.0 < log U < 0.0 in intervals of -0.3, -0.6, and -1.0 dex, and they vary grain content proportional with metallicity, though they claim this is a gross over simplification and cannot be justified, but it’s the simplest way to model the grain content. Their models show higher electron temperatures with higher grain content, and they mention that including grains in their models helps alleviate some of the temperature problem, though more work is needed.

Richardson et al. (2014) investigate the effects of density and ionization on AGN gas, and refer to many of the studies mentioned above. They mention that Komossa & Schulz drastically overestimate OI emission with high density values, which likely means that high density doesn’t exist. Instead, increasing density increases O emission but doesn’t affect Hα or Hβ emission, so different emission line ratios are observed. They also touch 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 are 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 include a model of 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 use 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 10.0, 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 integrate 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 a NLR, it is likely that the entire NLR isn’t homogenously high temperature and low metallicity, but there could be pockets of low temperature and high metallicity, and this method can simulate that variation.]] This study shows that varying density and ionizing flux in this manner, though likely a more accurate representation of the NLR, cannot alone provide a solution to the temperature problem.

Zhang Liang and Hammer (2013) mention that the temperature problem is still unsolved. They explain 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 (why successful? High Te?) (Dopita Sutherland) show LINER characteristics and not AGN.

They also explain 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 nH = 100 cm -3 and a power law index of -1.4. In addition, they include 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 conclude that “some strong [OIII] 4363 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] 4363 emission in AGN. (But they only show BPT for these galaxies, so can’t really say those models are reproducing the high Te that those galaxies show.)

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] 4363, 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 hydrogen density, ionization parameter and metallicity. However, our model will also vary grain content to explore the impact on electron temperature. We also investigate secondary excitation mechanisms such as turbulence and photoelectric heating via grains. 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. (Add that we want to find a solution that fits with all diagnostics, unlike ZLH where they showed the results on a BPT alone, we want to be able to say our models fit the data on all diagnostics. So what is considered success?)

[[[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. The same is likely true for shocks, that there are probably some clouds that are shocked and some that are not.]]]] Should this go in discussion/future work? Yes

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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]

Start bulleting Modeling Methods

Look at Dopita, Komossa, Groves, etc. and model after them

Talk about diagnostics that constrain parameters, like density constrained through SII ratio and Te by 4363, NII ratios. Stopping conditions and why, go into input file and write that out. Metals scales for nitrogen and helium?

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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