

A RELATION BETWEEN THE MID-INFRARED [Ne v] 14.3 μm AND [Ne III] 15.6 μm LINES IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

We present a strong correlation between the [Ne v] 14.3 μm and [Ne III] 15.6 μm emission lines arising from the narrow-line regions (NLRs) of active galactic nuclei (AGNs), spanning 4 orders of magnitude in luminosity. The data are compiled primarily from *Spitzer Space Telescope* observations of nearby Seyfert galaxies (median $z = 0.01$) and 3C radio sources (median $z = 0.52$). This correlation is consistent with earlier studies in the optical/UV bands showing that line ratios arising in the NLRs are remarkably constant across AGNs. We also show that the correlation allows only a very narrow range in ionization parameter for simple photoionization models. The observed correlation will place tight constraints on alternative models, which predict constant line ratios over a broader range in ionization parameter.

Subject headings: galaxies: active — galaxies: ISM — galaxies: nuclei — galaxies: Seyfert — line: formation — quasars: emission lines

1. INTRODUCTION

Forbidden emission lines provide many diagnostics of the ionized gas in the narrow-line regions (NLRs) of active galactic nuclei (AGNs). The ionization parameter $U = L_{\text{Ly}\alpha}/4\pi R^2 n_{\text{H}} c$ (Peterson 1997), the number of ionizing photons per hydrogen nucleus, is the primary determinant of emission-line strengths and ratios. A priori, we might expect it to vary over a wide range depending on the ionizing continuum and the gas density of an AGN. Yet surprisingly, the line ratios for AGNs vary little from object to object (Veilleux 1991). Unfortunately, the most accessible lines from the ground (e.g., [O III] $\lambda 5007$, [Ne III] $\lambda 3869$) are optical/UV lines that are strongly absorbed by dust (Antonucci 1993; Peterson 1997). To study the ionization parameter in a broader context, obscuration-insensitive diagnostics are required.

The mid-infrared is the ideal wavelength region to observe forbidden lines not only because extinction is low, but also because emission line strengths are high (Voit 1992). Lines such as [Ne v] 14.32 μm and [Ne III] 15.6 μm have not been extensively exploited, however, because they cannot be observed from the ground. The *Infrared Space Observatory* (*ISO*) provided the first glimpse of these lines from space (Sturm et al. 2002). The *Spitzer Space Telescope* (Werner et al. 2004) has provided the ability to gather a much larger sample of sources with a much broader range of fluxes and luminosities.

Using data primarily from *Spitzer*, we present here a previously unknown correlation between [Ne v] and [Ne III], which extends over 3 orders of magnitude in flux and 4 orders of magnitude in luminosity. These are particularly good lines to study for several reasons: they suffer little absolute extinction ($A_{15\ \mu\text{m}}/A_{\text{V}} = 0.015$; Cox 2000) and have near-zero differential extinction, they arise from the same element, and neon does not occur in or on grains.

2. THE SAMPLE

The *Spitzer* sample comprises 40 Seyfert 1 and 2 galaxies selected on their X-ray-determined hydrogen column density (V. Gorjian et al. 2007, in preparation), 77 3C radio sources (Haas et al. 2005; Ogle et al. 2006; Cleary et al. 2006), eight AGNs presented in Weedman et al. (2005), and three ultralu-

minous infrared galaxies (ULIRGs) observed by Armus et al. (2007). In addition, there are 29 objects observed by *ISO* (Sturm et al. 2002). The median redshift for the Seyfert sample is $z = 0.01$, while the median redshift for the 3C sources is $z = 0.52$. The errors are typically between 15% and 30%. Of these sources, a subsample of 53 objects was selected in which emission from both [Ne III] and [Ne v] was detected. Where an object is observed by both *Spitzer* and *ISO*, the *Spitzer* line flux densities are adopted.

All the *Spitzer* data were obtained using the Infrared Spectrograph (Houck et al. 2004) in the Long-Low mode, which covers the wavelength range from 14 to 38 μm with a resolution of $R \sim 60$ –120. Spectra for the Seyferts from V. Gorjian et al. (2007, in preparation) and the 3C sources from Cleary et al. (2006) were extracted from the basic calibrated data (BCD) images provided by the *Spitzer* Science Center, using the Spectroscopy Modeling and Analysis Tool (SMART; Higdon et al. 2004). Narrow extraction apertures were used in order to maximize the signal-to-noise ratio for the 3C objects and to reject the host-galaxy contribution for the Seyferts, some of which were resolved by the IRS. Line fluxes for the other objects were obtained from the literature.

2.1. The Infrared Correlation

Figure 1 shows the correlation between the fluxes of the [Ne v] and [Ne III] lines (*left*) and the same correlation for the luminosities¹ of the lines (*right*); the values are given in Table 1. Note the tight correlation over 4 orders of magnitude in line luminosity for both type 1 and 2 sources.

The data are well fit by the line $\log(L_{[\text{Ne III}]} / 10^{33}) = 0.30 + 0.89 \log(L_{[\text{Ne v}]} / 10^{33})$ with 0.2 dex scatter in log space and that has a power-law form of $(L_{[\text{Ne III}]} / 10^{33}) = 2.0(L_{[\text{Ne v}]} / 10^{33})^{0.89}$ W sr⁻¹. In all cases where [Ne v] is detected, the [Ne III] detection or upper limit is consistent with the observed correlation. NGC 3079, which was observed using *Spitzer* by Weedman et al. (2005), is the most significant outlier, with ≈ 5 times more luminous [Ne III] emission than expected from the observed [Ne v]. However, based on the [O IV] 25.9 μm /[Ne II] 12.8 μm AGN/starburst mixing model of Sturm et al. (2002) this object

¹ Based on distances using $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

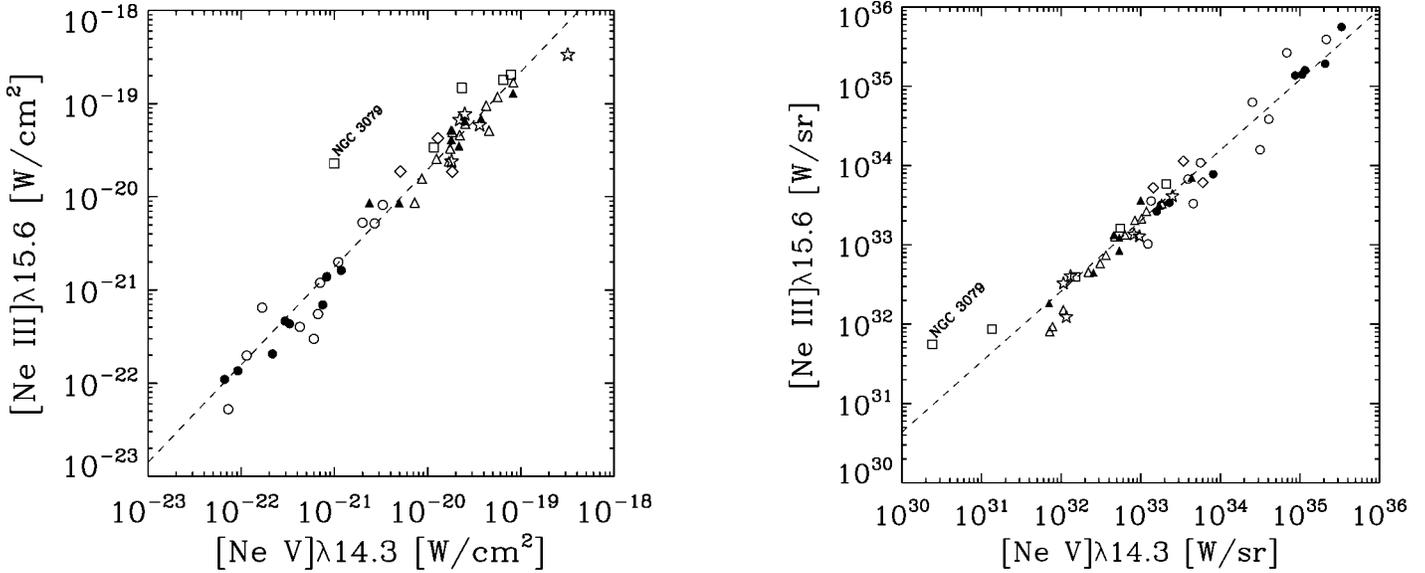


FIG. 1.—*Left*: [Ne III] flux density vs. [Ne V] flux density with a line fit (*dashed line*). *Circles*: 3C radio sources from Haas et al. (2005), Ogle et al. (2006), and Cleary et al. (2006). *Triangles*: Seyfert galaxies from V. Gorjian et al. (2007, in preparation). *Squares*: AGNs observed by Weedman et al. (2005). *Stars*: *ISO* observations from Sturm et al. (2002). *Diamonds*: ULIRGs observed by Armus et al. (2007). *Filled symbols*: Type I objects. *Open symbols*: Type II objects. *Right*: [Ne III] luminosity vs. [Ne V] luminosity with a line fit (*dashed line*).

has the lowest AGN contribution of the entire subsample and so the excess [Ne III] emission may be due to star formation.

2.2. The Ultraviolet Correlation

The higher redshift sources in our sample bring two UV doublets of [Ne III] and [Ne V], [Ne III] $\lambda\lambda 3869, 3968$ and [Ne V] $\lambda\lambda 3346, 3426$, into the visible wavelength range where they can be more easily measured. Lawrence et al. (1996) measured the UV lines of 3C sources (a few of which overlap with our sample) and they show a similar relation to the IR neon lines, although with a larger scatter (see, e.g., Fig. 2). The differential extinction across the UV lines is relatively low,

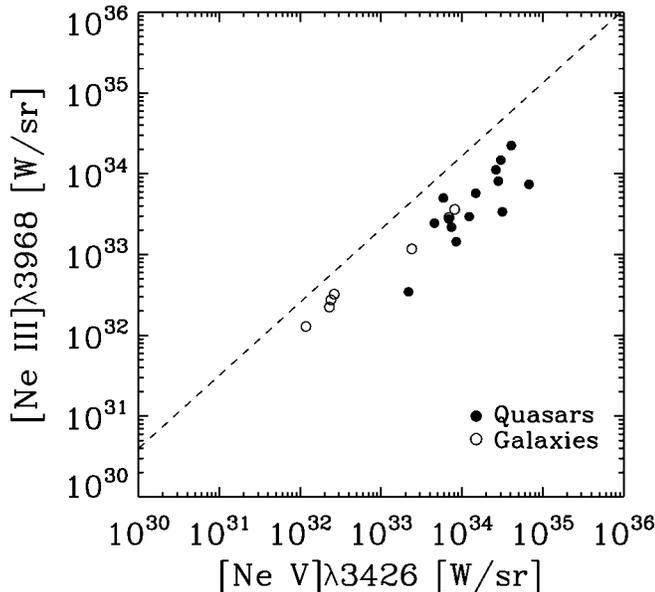


FIG. 2.—[Ne III] $\lambda 3968$ vs. [Ne V] $\lambda 3426$ line luminosity for 3C quasars (*filled circles*) and radio galaxies (*open circles*). The fit to the IR line luminosities (see Fig. 1) is plotted as a *dashed line*.

e.g., $A_{3868}/A_{3425} \sim 1.06$ (Cox 2000), and so is unlikely to be the cause of the greater scatter.

3. PHOTOIONIZATION MODELS

We have used version C06.02 of the Cloudy photoionization code (Ferland et al. 1998) to predict the [Ne] emission line flux density for a constant-density cloud with inner radius of 10^{30} cm and a power-law ionizing energy spectrum $\propto \nu^\alpha$ for $10 \mu\text{m} < \nu < 50 \text{ keV}$ ($\propto \nu^{5/2}$ and $\propto \nu^{-2}$ for lower and higher frequencies, respectively). In Figure 3 we show the results for a grid of ionization parameter U and hydrogen density values with $\alpha = -1.0$ and $\alpha = -1.5$. Since U is the ratio of the number density of ionizing photons to the number density of hydrogen atoms, it depends on the luminosity of the ionizing source, the distance from that source, and the density of the hydrogen gas. As noted by Voit (1992) the [Ne V]/[Ne III] line ratio is predicted to vary as U^2 . From Figure 3 we see that over a broad range of hydrogen densities ($n_{\text{H}} = 10^2 - 10^6 \text{ cm}^{-3}$) and for an ionization index ranging from -1.0 to -1.4 , the observed correlation between [Ne III] and [Ne V] traces a rel-

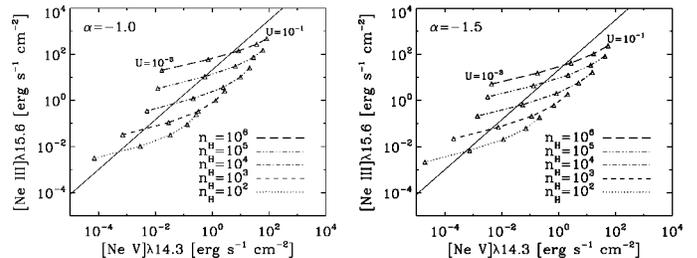


FIG. 3.—Predicted [Ne III] $15.6 \mu\text{m}$ and [Ne V] $14.3 \mu\text{m}$ flux density (at the inner face of the cloud, a distance of 10^{30} cm from the ionizing source) for a Cloudy constant-density photoionization model with $\log U = \{-3.0, -2.5, -2.0, -1.5, -1.0\}$ and $\log n_{\text{H}} = \{2, 3, 4, 5, 6\}$ for an ionizing index $\alpha = -1.0$ (*left*) and $\alpha = -1.5$ (*right*). Each possible combination of $\{U, n_{\text{H}}\}$ is indicated by a triangle. The fit to the observed line flux densities (see Fig. 1) is plotted as a solid line. Note that the observed correlation passes through almost the same U for densities ranging from $n_{\text{H}} = 10^2$ to 10^4 cm^{-3} .

TABLE 1
NEON LINE FLUXES AND LUMINOSITIES

Name	z	[Ne v] (10^{-20} W cm $^{-2}$)	[Ne III] (10^{-20} W cm $^{-2}$)	[Ne v] (10^{33} W sr $^{-1}$)	[Ne III] (10^{33} W sr $^{-1}$)	AGN Type	Sample
3C 33	0.060	0.20	0.53	1.35	3.58	2	1
3C 55	0.735	0.11	0.20	214	389	2	1
3C 79	0.256	0.01	0.02	1.82	3.17	2	2
3C 109	0.306	0.01	0.01	1.59	2.64	1	2
3C 120	0.033	2.17	3.53	4.34	7.06	1	3
3C 184	0.994	0.02	0.07	68.5	264	2	4
3C 196	0.871	0.03	0.05	87.3	137	1	4
3C 234	0.185	0.33	0.82	25.3	62.9	2	1
3C 244.1	0.428	0.06	0.03	31.6	15.8	2	1
3C 249.1	0.311	0.01	0.01	2.3	3.39	1	2
3C 286	0.849	0.08	0.07	207	192	1	4
3C 295	0.461	0.01	0.01	4.58	3.32	2	2
3C 309.1	0.904	0.03	0.04	107	141	1	4
3C 321	0.096	0.07	0.06	1.23	1.03	2	2
3C 330	0.549	0.04	0.04	40.6	38.4	2	4
3C 334	0.555	0.12	0.16	116	159	1	4
3C 343	0.988	0.08	0.14	334	559	1	4
3C 351	0.371	0.02	0.02	8.14	7.78	1	2
3C 381	0.161	0.07	0.12	3.93	6.74	2	1
3C 433	0.102	0.27	0.52	5.63	10.9	2	1
Centaurus A	0.002	2.31	14.8	0.01	0.09	2	5
Circinus	0.001	31.7	33.5	0.12	0.12	2	6
ESO 103-G035	0.013	1.79	4.1	0.54	1.23	1	3
IC 4329a	0.016	3.72	6.95	1.7	3.18	1	3
IC 5135	0.016	2.20	4.6	1.02	2.13	2	3
IR 07145-2914	0.006	8.29	16.8	0.37	0.74	2	3
IR 05189-2524	0.043	1.84	1.86	6.02	6.1	2	7
MCG -6-30-15	0.008	0.73	0.86	0.08	0.09	2	3
MCG -2-58-22	0.048	0.24	0.86	1.0	3.66	1	3
Mrk 3	0.014	6.45	17.9	2.1	5.82	2	5
Mrk 273	0.038	1.29	4.27	3.43	11.4	2	7
Mrk 509	0.034	0.86	1.56	1.83	3.32	2	3
Mrk 573	0.017	1.8	2.4	0.96	1.28	2	6
Mrk 1066	0.012	1.78	5.2	0.46	1.33	1	3
NGC 1068	0.004	97	160	2.5	4.12	2	6
NGC 1365	0.005	2.5	7.7	0.13	0.40	2	6
NGC 1386	0.003	4.54	5.11	0.07	0.08	2	3
NGC 2273	0.006	1.68	2.38	0.11	0.15	2	3
NGC 3079 ^a	0.004	0.10	2.28	0.002	0.06	2	5
NGC 3393	0.013	4.24	9.5	1.18	2.64	2	3
NGC 3783	0.010	1.74	3.3	0.31	0.59	2	3
NGC 4151	0.003	7.77	20.4	0.15	0.39	2	5
NGC 4388	0.008	5.6	11.8	0.63	1.34	2	3
NGC 4507	0.012	1.84	4.96	0.47	1.27	2	3
NGC 4939	0.010	1.24	2.55	0.22	0.45	2	3
NGC 5135	0.014	2.52	6.07	0.84	2.03	2	3
NGC 5506	0.006	8.2	12.9	0.54	0.85	1	3
NGC 5548	0.017	0.49	0.86	0.26	0.45	1	3
NGC 5643	0.004	2.51	6.54	0.07	0.18	1	3
NGC 7469	0.016	1.16	3.4	0.55	1.62	2	5
NGC 7582	0.005	2.2	6.7	0.11	0.33	2	6
PKS 2048-57	0.011	3.6	5.9	0.82	1.35	2	6
UGC 5101	0.039	0.51	1.87	1.44	5.26	2	7

^a NGC 3079's [Ne v] emission was only detected in one nod position and that value is presented here.

SAMPLES.—(1) Ogle et al. 2006; (2) Haas et al. 2005; (3) V. Gorjian et al. 2007, in preparation; (4) Cleary et al. 2006; (5) Weedman et al. 2005; (6) Sturm et al. 2002; (7) Armus et al. 2007.

atively narrow range in U , $-2.8 < \log U < -2.0$. For low densities ($n_{\text{H}} < 10^4 \text{ cm}^{-3}$) more typical of NLRs, $\log U$ spans an even narrower range, $-2.8 < \log U < -2.5$.

Although we infer a narrow range of U in our sample of AGNs based on a simple, constant-density ionization model, this model fails to explain how the ionization parameter of different AGNs could be so constrained. Dopita et al. (2002) have developed an alternative, dusty, radiation-pressure-dominated photoionization model in order to account for the constancy of line ratios from the NLRs of Seyfert galaxies without requiring such a narrow range in U . Figure 4 shows the pre-

dicted [Ne III] $15.6 \mu\text{m}$ /[Ne v] $14.3 \mu\text{m}$ line ratio for such a model, taken from Groves et al. (2004); for $-1.6 \leq \log U \leq 0$, the line ratio is predicted to be constant, independent of U .

4. SUMMARY AND CONCLUSIONS

We have presented a strong correlation between the [Ne v] $14.3 \mu\text{m}$ and [Ne III] $15.6 \mu\text{m}$ emission lines that spans 4 orders of magnitude in line luminosity. This relation holds even though the AGNs range in type from Seyfert 1s and 2s to quasars and radio galaxies. For 3C radio sources that have their UV neon

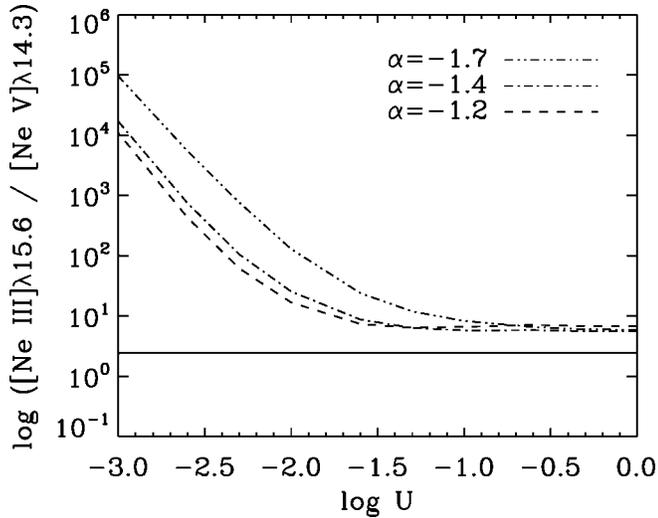


FIG. 4.—Predicted [Ne III] 15.6 μm /[Ne V] 14.3 μm line ratio vs. ionization parameter U for a dusty, constant-pressure model, with an ionizing index of $\alpha = \{-1.2, -1.4, -1.7\}$ and $n_{\text{H}} = 10^3$, from Groves et al. (2004). The mean observed [Ne III]/[Ne V] for our sample of 50 AGNs is indicated by a solid line. The model predicts a line ratio independent of U for $-1.6 < \log U < 0$.

lines redshifted so that they can be observed from the ground, a similar relation holds but with a slightly larger scatter.

The nature of the process that maintains similar line ratios over a variety of different AGNs has been a question for some time. These line ratios imply a narrow range of ionization pa-

rameter for simple photoionization models, yet in principle, the ionizing luminosity, the distance to the gas, and its density are free to take on a broad range of values. This problem is emphasized by the observed correlation which, for a constant-density photoionization model and densities typical of NLRs, implies an ionization parameter in the range $-2.8 < \log U < -2.5$ across a sample of AGNs spanning 4 orders of magnitude in luminosity. Dusty, radiation-pressure-dominated photoionization models have been proposed by other investigators (Dopita et al. 2002; Groves et al. 2004) that predict constant line ratios without requiring a narrow range in U . The observed correlation will place even tighter constraints on such models.

The observed correlation also unifies type 1 and 2 objects over approximately 4 orders of magnitude in line luminosity, demonstrating that there is a common underlying physics at work. This suggests that by studying nearby, low-luminosity objects such as Seyferts, whose NLRs can be resolved, a great deal of knowledge can be gained about the NLRs of far away, unresolved, luminous quasars.

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