Discovery of a strong Baldwin effect in mid-infrared AGN lines*

S. F. Hönig1, A. Smette2, T. Beckert1, H. Horst3,4, W. Duschl5, P. Gandhi5, M. Kishimoto1, and G. Weigelt1

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
2 European Southern Observatory, Casilla 19001, Santiago 19, Chile
3 Institut für Theoretische Physik und Astrophysik, Christian-Albrechts-Universität zu Kiel, Leinbacherstr. 15, 24098 Kiel, Germany
4 Zentrum für Astronomie, ITA, Universität Heidelberg, Albert-Ueberle-Str. 2, 69120 Heidelberg, Germany
5 RIKEN Cosmic Radiation Lab, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

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ABSTRACT

We present the discovery of a Baldwin effect in 8 nearby Seyfert galaxies for the three most prominent mid-infrared forbidden emission lines observable from the ground that are commonly found in AGN, [Ar iii] λ 8.99 μm, [S iv] λ 10.51 μm, and [Ne iii] λ 12.81 μm. The observations were carried out using the VLT/VISIR imager and spectrograph at the ESO/Paranal observatory. The bulk of the observed line emission comes from the inner <0.4" which corresponds to spatial scales <100 pc in our object sample. The correlation index is approximately −0.6 without significant difference among the lines. This is the strongest anti-correlation between line equivalent width and continuum luminosity found so far. In the case of Circinus, we show that despite the use of mid-infrared lines, obscuration by either the host galaxy or the circumnuclear dust torus might affect the equivalent widths. Given the small observed spatial scales from which most of the line emission emanates, it is unclear how these observations fit into the favored “disappearing NLR” scenario for the narrow-line Baldwin effect.

Key words. Galaxies: Seyfert – Galaxies: nuclei – Infrared: galaxies – Quasars: emission lines – X-rays: galaxies

1. Introduction

The Baldwin effect, a negative correlation between equivalent width, \( W_i \), and continuum luminosity, \( L \), is commonly found in broad UV/optical emission lines of AGN. Initially, it was reported for the C iv(λ1549) line (Baldwin 1977) for which \( W_i \propto L^{-1/2} \), but later also found in emission lines of many other species for which the strength of the correlation depends on the ionization potential of the respective line (e.g. Dietrich et al. 2002). Although the Baldwin effect is well established, its physical origin is still a matter of debate. A common explanation refers to the spectral shape of the ionizing continuum which appears softer in the inner <0.4" which corresponds to spatial scales <100 pc in our object sample. The correlation index is approximately −0.6 without significant difference among the lines. This is the strongest anti-correlation between line equivalent width and continuum luminosity found so far. In the case of Circinus, we show that despite the use of mid-infrared lines, obscuration by either the host galaxy or the circumnuclear dust torus might affect the equivalent widths. Given the small observed spatial scales from which most of the line emission emanates, it is unclear how these observations fit into the favored “disappearing NLR” scenario for the narrow-line Baldwin effect.

In this letter, we present our discovery of a strong Baldwin effect in nearby Seyfert galaxies for the most prominent narrow emission lines that are present in AGN mid-infrared spectra and observable from the ground, in particular [Ar iii] λ 8.99 μm, [S iv] λ 10.51 μm, and [Ne iii] λ 12.81 μm. The Baldwin Effect in these mid-infrared forbidden lines (hereafter: iNLBE) is much stronger than for any other as yet observed. In Sect 2 we report on details about the VLT/VISIR observations. In Sect 3 the results are presented, followed by a discussion of our finding in Sect 4. This paper (hereafter: paper I) presents first results on line emission of our larger campaign using VLT/VISIR which is dedicated to mid-infrared spectroscopy of nearby AGN at high spatial resolution. A forthcoming paper (hereafter: paper II) will deal with the mid-infrared continuum emission of AGN. In the following, we will use cosmological parameters \( H_0 = 73 \text{ km/}(\text{s Mpc}) \), \( \Omega_M = 0.72 \), and \( \Omega_\Lambda = 0.24 \) (Spergel et al. 2007).

2. Observations

We used the mid-infrared imager and spectrograph VISIR located at the 8 m UT3 telescope of the ESO/Paranal observatory. With VISIR, we observed a sample of 8 nearby AGN of which 5 are Seyfert 2 (S1h, S1i, S2) and 3 are Seyfert 1 (S1.0, S1.5) galaxies. The 8 − 13 μm N-band spectra were acquired in low spectral resolution mode (R~300), for which 4 different wavelength settings centered at 8.5, 9.8, 11.4, and 12.4 μm have to be combined for each object. With VISIR, the achieved spatial...
In Table 1, we present extracted correlations for our sample of nearby AGN as listed in Table 1. The fitted correlations $W_{\lambda} \propto L_X^{-0.75 \pm 0.11}$ for [Ar\textsc{iii}] (blue dashed line; $\rho_{\text{Spearman}} = -0.91$, significance 0.002), and $W_{\lambda} \propto L_X^{0.66 \pm 0.12}$ for [S\textsc{iv}] (red dashed-dotted line; $\rho_{\text{Spearman}} = -0.79$, significance 0.04) are shown. Circinus (gray symbols) is outlying probably due to significant obscuration by dust in the host galaxy or the circumnuclear dust torus (see Fig. 4).

resolution in this wavelength range is $0''25 - 0''39$, which is a factor 2 -- 4 smaller than the used slit widths of $0''75 - 1''0$ making slit losses negligible. The resulting spectra were extracted using the standard VISIR CPL pipeline (V3.0.0) and calibrated by a number of generic standard stars. For NGC 4507, a single standard star observed within the same night has been used for calibration. In addition to the 8 objects, archival VISIR data of NGC 1068 and NGC 253 has been downloaded, extracted, and calibrated in the same way. A more detailed description of the observations will be presented in paper II. NGC 4593 has been observed only in the 8.5 and 9.8 $\mu$m settings, corresponding to a restframe wavelength coverage of approximately 7.9 -- 10.4 $\mu$m. As a result, only [Ar\textsc{iii}](18.99 $\mu$m) is seen in the combined spectrum, giving $W_{\lambda}$ data in this line on a total of 8 objects. For [S\textsc{iv}](10.51 $\mu$m), and [Ne\textsc{ii}](12.81 $\mu$m), equivalent widths of 7 objects is available.

### 3. The Baldwin effect in forbidden mid-IR lines

#### 3.1. Results

In Table 1 we present extracted $W_{\lambda}$ of all three lines. For all objects, the line emission was strongly peaked towards the nucleus. Except for the emission in the most nearby objects NGC 1068 ($\sim 10\%$ extension in [S\textsc{iv}] with respect to the continuum PSF) and Circinus ($\sim 50\%$ extension in [S\textsc{iv}] and [Ne\textsc{ii}]), no spatial extension was detected in the continuum and the lines. The reduction was done in a way that even for these extended objects, almost no line flux is lost by the extraction window. The errors on $W_{\lambda}$ represent the uncertainty due to the determination of the shape of continuum emission underlying the emission line. This uncertainty is in part due to the presence of sky lines in those spectra which were taken under unfavorable atmospheric conditions (e.g. high amount of precipitable water vapor). This affects the [Ne\textsc{ii}] line the most since strong atmospheric bands are present between 12.4 -- 12.7 $\mu$m. On the other hand, the error bars of the [Ar\textsc{iii}] line are predominantly caused by the general weakness of the line with respect to the continuum.

In addition to the line $W_{\lambda}$s, Table 1 lists (absorption-corrected) 2 -- 10 keV X-ray luminosities, $L_X$, for our sample of AGN. These are taken as a measure for the ionizing continuum luminosity since the UV/optical AGN emission of our type 2 sources is heavily affected by dust absorption from the putative circumnuclear dust torus. Unfortunately, 3 of our objects are Compton-thick to the X-ray emission (NGC 1068, Circinus, and ESO 428--G14). For these objects, we estimated the nuclear X-ray luminosity by extracting the 12 $\mu$m continuum emission from our spectra, which will be presented in paper II, and translating the corresponding spectral luminosity into $L_X$ using the most recent version of the $L_{\text{MIR}} - L_X$-correlation for AGN as established from VISIR observations with similar spatial resolution (Horst et al. 2008). We adopt 50% of error on $L_X$ for these objects.

In Figs. 1 & 2, we show the measured $W_{\lambda}$ of [Ar\textsc{iii}], [S\textsc{iv}], and [Ne\textsc{ii}] versus $L_X$. The trend of smaller $W_{\lambda}$ with luminosity is evident. As an illustration, the spectral regions around the [Ar\textsc{iii}] and [S\textsc{iv}] lines are presented in Fig. 3 for NGC 3227 (log $L_X = 42.4$), MCG--5--23--16 (log $L_X = 43.2$), and NGC 1068 (log $L_X =$...
43.7). A statistical analysis of the correlation for our sample shows Spearman ranks $\rho_{\text{Spearman}} = -0.75 \ldots -0.9$ with significance levels in the range of $0.2 - 5 \times 10^{-2}$. Despite the limited number of objects and luminosity coverage, correlations evolving out of the data can be confidently established. For BLBE and oNLBE studies, higher significance is achieved by averaging spectra of different objects within a narrow luminosity range. This overcomes peculiarities of individual objects (e.g. Croom et al. 2002). We aim for observations of a larger sample to make similar studies for the presented iNLBE. It is important to note that no correlation of $W_l$ with AGN distance, $D_l$, is present in our sample ($\rho_{\text{Spearman}} < 0.25$, significance $> 0.6$ for all lines).

As of yet, only one other study mentions a possible Baldwin effect in the mid-infrared. In an AAS abstract, Keremedjiev & Hao (2006) presented the detection of a Baldwin effect for the [S\textsc{iv}] line in AGN data obtained by the Spitzer satellite. They also note indications of a Baldwin effect for [Ne\textsc{ii}], admitting that their study is suffering from the low spatial resolution of the Spitzer data that they used. In the available abstract, nothing is mentioned about a slope or the scatter of the anti-correlation. Here, we demonstrate that the Baldwin effect of both the [S\textsc{iv}] and [Ne\textsc{ii}] line, and in addition the [Ar\textsc{iii}] line, is quite significant and strong — when using high spatial resolution data, even with a small object sample. Thus, high spatial resolution appears to be crucial.

### 3.2. Relation to $M_{\text{BH}}$ and $L_{\text{Edd}}$

For the three type 1 AGN in our sample, black hole masses, $M_{\text{BH}}$, have been estimated based on reverberation mapping data. We adopt black hole masses for NGC 3227 ($\log M_{\text{BH}}(M_\odot) = 7.63 \pm 0.31$) and NGC 3783 ($\log M_{\text{BH}} = 7.47 \pm 0.08$) from Onken et al. (2004), and $\log M_{\text{BH}} = 6.99 \pm 0.10$ for NGC 4593 from Denney et al. (2004). In addition, the black hole mass of the Seyfert 2 galaxy NGC 1068 could be determined by MASER cloud kinematics as $\log M_{\text{BH}} \approx 7.0$ (Greenhill et al. 1996). For these four AGN, we analyzed the dependence of the equivalent widths of the [Ar\textsc{iii}] line on $M_{\text{BH}}$. A statistical test shows no evidence correlation for our limited sample of objects and the small coverage of black hole masses ($\rho_{\text{Spearman}} = 0.40$, significance 0.6, for a nominal fit $W_l([\text{Ar\textsc{iii}}]) \propto M_{\text{BH}}^{0.5 \pm 0.7}$). Subject to the limitations, this indicates a fundamental difference of the iNLBE as compared to the BLBE for which such an anti-correlation has been found (Warner et al. 2004).

By using bolometric correction to the X-ray luminosities listed in Table 1 (Marconi et al. 2004), it is possible to estimate the Eddington ratio, $L_{\text{Edd}}$, of four AGN with known $M_{\text{BH}}$. A statistical test for a correlation between $W_l([\text{Ar\textsc{iii}}])$ and $L_{\text{Edd}}$ reveals a Spearman rank $\rho_{\text{Spearman}} = -0.8$ with a significance of 0.2 for the relation $W_l([\text{Ar\textsc{iii}}]) \propto L_{\text{Edd}}^{-0.5 \pm 0.17}$. Thus, our limited sample doesn’t allow us to firmly establish a correlation, but a negative dependence of $W_l$ on $L_{\text{Edd}}$ is indicated.

### 3.3. The case of Circinus

We excluded Circinus from all analysis of the correlations. As can be seen in Figs. 1 & 2 the $W_l$’s of all three mid-infrared lines deviate significantly from the nominal fit to the other AGN.
Although it could be a resolution effect (Circinus is the nearest AGN in the sample), NGC 1068 has about the same spatial resolution when scaled for the different luminosities (scaling $r \propto L^{1/2}$). Moreover, we did not detect extended emission in the lines down to $\sim 5\%$ of the peak flux. This gives us some confidence to reject that a significant amount of line flux is unresolved and lost in the noise.

Circinus is known for strong dust extinction towards the nucleus by dust lanes in both the host and our own Galaxy. In Fig. 4 we plot the deviation from the nominal correlation with X-ray luminosity (as given in Figs. 11 & 12) of each line against the depth of the silicate feature. Circinus shows the strongest deviations from all correlations and, at the same time, has the deepest silicate feature. It is deeper than in any other type 2 AGN in our sample. In case of foreground extinction (host or our galaxy), we expect that the flux within the lines is reduced in the same way without a change in $W_I$. On the other hand, if part or all of the line emission is originating from inward of the torus, the extinction in the lines could be much stronger in a more or less edge-on torus geometry. Given the fact that the bulk of line emission in all other AGN is coming from the unresolved point source, such a scale and inclination effect appears possible. Strong extinction towards the NLR based on mid-infrared spectra of Circinus was also noted by Roche et al. (2006).

4. Discussion and conclusions

4.1. A comparison to UV/optical lines

The negative correlations in the [Ar\textsc{iii}], [S\textsc{iv}], and [Ne\textsc{ii}] lines as observed with VLT/VISIR is much stronger than any known Baldwin effect in optical/UV broad or narrow lines. This is remarkable since the spatial resolution in the optical of the most recent studies should be similar or even better than what is achieved in the mid-infrared with the VLT. In UV/optical lines, a trend for larger correlation slopes with increasing ionization potential is observed (e.g. Dietrich et al. 2002). The potential of the presented lines is in the range of 40–47 eV and, thus, comparable to some of the optical/UV lines. From the optical/UV lines, slopes of the order of $-0.1$ to $-0.2$ would be expected. The measured slope of the mid-infrared lines deviates by at least $4-\sigma$ from that expectation (except [Ne\textsc{ii}] w/o NGC 253: $-2\sigma$).

In Sect 3.2 we found some negative trend of $W_I([\text{Ar\textsc{iii}}])$ with $L_{\text{bol}}$, but possibly not with $M_{\text{BH}}$. If confirmed, this is in contrast to the observed and theoretically-expected behavior of the broad lines (e.g. Wandel 1999, Warner et al. 2004). Thus, the unsettled correlation with $M_{\text{BH}}$ might imply that the iNLBE has a different physical origin than the BLBE, in particular questioning the relevance of the $M_{\text{BH}}$-dependence of the ionising continuum on the mid-infrared narrow-line emission.

4.2. Implications for the origin of the iNLBE

One suggestion for the origin of the oNLBE relates to the size scaling of the narrow-line region (NLR), for which a luminosity dependence $R_{\text{NLR}} \propto L^{0.5}$ has been found (Bennert et al. 2002). As a consequence, the NLR of luminous sources may reach galactic size scales and, thus, lose its gas. This scenario is often referred to as the “disappearing NLR” (Croom et al. 2002, Netzer et al. 2004). For the mid-infrared lines, we find that the main portion of their emission is not coming from a spatially-extended region, e.g. as for [O\textsc{ii}] in the optical, but from scales smaller than 100 pc. If the lack of line emission in Circinus is really an inclination-dependent obscuration effect, then the involved scales are significantly smaller. Since it is difficult to imagine how the NLR could disappear on these scales, the iNLBE probably requires a different explanation. This explanation needs to explain, in particular, (1) the steepness of the correlation of the presented lines, and (2) the fact that the mid-infrared lines do not follow the ionisation potential-dependence as observed in optical lines. Possible mechanisms might involve a luminosity-dependent increase of density in the inner NLR (thus suppressing forbidden line emission).
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