The Mid-Infrared $[\text{S}\,\text{iv}] / [\text{Ne}\,\text{ii}]$ versus $[\text{Ne}\,\text{iii}] / [\text{Ne}\,\text{ii}]$ Correlation

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ABSTRACT

The mid-infrared ratio $[\text{Ne}\,\text{ii}]_{15.6\mu m} / [\text{Ne}\,\text{ii}]_{12.8\mu m}$ is a strong diagnostic of the ionization state of emission line objects, due to its use of only strong neon emission lines only weakly affected by extinction. However this ratio is not available to ground-based telescopes as only a few spectroscopic windows are available in the MIR. To deal with this problem we aimed to verify if there exists a conversion law between ground-accessible, strong MIR line ratio $[\text{S}\,\text{iv}] / [\text{Ne}\,\text{ii}]$ and the diagnostic $[\text{Ne}\,\text{iii}] / [\text{Ne}\,\text{ii}]$ ratio that can serve as a reference for future ground-based observations. We collated the $[\text{S}\,\text{iv}]_{10.5\mu m}$, $[\text{Ne}\,\text{ii}]_{12.8\mu m}$, $[\text{Ne}\,\text{iii}]_{15.6\mu m}$ and $[\text{S}\,\text{iii}]_{18.7\mu m}$ emission line fluxes from a wide range of sources in the rich Spitzer and ISO archives, and compared the $[\text{Ne}\,\text{iii}] / [\text{Ne}\,\text{ii}]$, $[\text{S}\,\text{iv}] / [\text{S}\,\text{iii}]$, and $[\text{S}\,\text{iv}] / [\text{Ne}\,\text{ii}]$ ratios. We find a strong correlation between the $[\text{S}\,\text{iv}] / [\text{Ne}\,\text{ii}]$ and $[\text{Ne}\,\text{iii}] / [\text{Ne}\,\text{ii}]$ ratio, with a linear fit of $\log ([\text{Ne}\,\text{iii}] / [\text{Ne}\,\text{ii}]) = 0.81 \log ([\text{S}\,\text{iv}] / [\text{Ne}\,\text{ii}]) + 0.36$, accurate to a factor of $\sim 2$ over four orders of magnitude in the line ratios. This demonstrates clearly the ability of ground-based infrared spectrographs to do ionization studies of nebulae.

Key words: Infrared:ISM–H II Regions–Planetary Nebulae–Galaxies:starburst

1 INTRODUCTION

The mid-infrared spectrum (MIR, $\sim 3-100\mu m$) hosts a range of important diagnostic fine-structure emission lines. Due to the much lower dust opacity at these long wavelengths, the emission lines are significantly less affected by extinction than ultraviolet or optical lines (see e.g. Draine 2003). Thus these lines are able to probe ionized regions that lie behind dense obscuring clouds or even deep within galaxy centers, giving insights into the regions where massive star formation events actually occur, or heavily obscured active galactic nuclei (AGN) can exist.

One of the more useful facets of this wavelength regime is that it includes emission lines from several ions of the same species, in particular strong lines from neon and sulphur. These lines can be used as strong diagnostics of the ionization state of the emitting gas as, being from the same species, there is no direct dependence on the gas phase abundances, and the different ionization potentials allow the observer to trace the hardness of the ionizing spectrum (see e.g. Dopita & Sutherland 2003). Lines ratios such as $[\text{Ne}\,\text{ii}]_{14.3\mu m} / [\text{Ne}\,\text{ii}]_{12.8\mu m}$, $[\text{Ne}\,\text{iii}]_{15.6\mu m} / [\text{Ne}\,\text{ii}]_{12.8\mu m}$, and $[\text{S}\,\text{iv}]_{10.5\mu m} / [\text{S}\,\text{iii}]_{18.7\mu m}$ have been used to diagnose the presence of deeply buried AGN (e.g. Sturm et al. 2002, Armus et al. 2006) and as indicators of the ages of starbursts (e.g. Achtermann & Lacy 1995, Thornley et al. 2000).

The major drawback of the MIR emission lines as diagnostics is their accessibility, with the full range of lines only available to spectrographs aboard space-borne telescopes like the short wavelength spectrograph (SWS, de Graauw et al. 1996) aboard the Infrared Space Observatory (ISO, Kessler et al. 1996) and the infrared spectrograph (IRS, Houck et al. 2004) aboard the Spitzer Space Telescope (Werner et al. 2004). While MIR instruments on ground based telescopes can provide higher spatial and spectral resolution, only a sparse number of MIR bands are available due to the opaqueness of the Earth’s atmosphere in the mid-infrared (M-band: $\sim 4.5 - 5.5\mu m$, N-band: $\sim 8.5 - 13\mu m$, and Q-band: $\sim 17 - 23\mu m$). As a result, the $[\text{Ne}\,\text{iii}]_{15.6\mu m}$ line is inaccessible from the ground and therefore recent high-resolution studies have resorted to the ratio $[\text{S}\,\text{iv}]_{10.5\mu m} / [\text{Ne}\,\text{ii}]_{12.8\mu m}$, as a diagnostic (e.g. Snijders et al. 2007), in a similar manner to earlier aircraft-borne IR telescope studies (e.g. Achtermann & Lacy 1995). However the question remains whether the use of this ratio as a proxy for the ionization sensitive $[\text{Ne}\,\text{iii}]_{15.6\mu m} / [\text{Ne}\,\text{ii}]_{12.8\mu m}$ ratio is justified. While photoionization theory clearly indicates that there will be a correlation between these ratios, the dependence of the line emission on often unknown physical parameters make the accuracy of this correlation uncertain. As an example, the $[\text{S}\,\text{iv}] / [\text{Ne}\,\text{ii}]$ ratio is directly proportional to the sulfur to neon abundance ratio, while the $[\text{Ne}\,\text{iii}] / [\text{Ne}\,\text{ii}]$ will be almost unaffected by any changes in the relative abundances. Similarly, with an excitation potential of 34.79 eV, $[\text{S}\,\text{iii}]$ is sensitive to lower energy photons than $[\text{Ne}\,\text{ii}]$, which has an excitation potential of 40.96 eV and will not exist in photoionized gas when there are no photons above this limit.

In this letter we use archival ISO and Spitzer observations of a range of astrophysical objects to demonstrate that such a correlation does exist and derive a simple conversion law for these ratios. We mention possible systematics with the determination of these ratios and discuss the origin of the observed correlation. As a final note...
we recommend the application of these results in future (ground-based) observations.

2 OBSERVATIONAL DATA

The strong, diagnostic, MIR emission lines \([\text{S}\,\text{iv}]/\text{[Ne}\,\text{ii}]\) and \([\text{Ne}\,\text{ii}]/\text{[Ne}\,\text{iii}]\) have been detected and characterised in a broad range of astrophysical objects, from nearby galactic H\,\text{n} regions to ultraluminous infrared galaxies (ULIRGs). To determine the connection between the \([\text{S}\,\text{iv}]/\text{[Ne}\,\text{ii}]\) and \([\text{Ne}\,\text{ii}]/\text{[Ne}\,\text{iii}]\) ratios we have extracted from the recent literature the fluxes of these four emission lines. While not exhaustive, the sample of 355 emission line objects is representative of the range of sources from which these lines arise, covering a range of physical parameters, such as source morphology and geometry, nature of the ionizing sources and metal and dust abundances.

A list of the different source types in our sample and the relevant papers from which we extracted these is given in Table 1. Included in the sample are sources ionized by massive stars, both small scale (H\,\text{n} regions and extragalactic H\,\text{n} regions) and large scale (blue compact dwarfs (BCDs), starburst galaxies (SB), and Ultra Luminous IR galaxies (ULIRGs)), planetary nebulae (PNe), which are ionized by white dwarfs, and active galactic nuclei (AGN).

Table also includes the average percentage uncertainty in the \([\text{Ne}\,\text{ii}]\) line as given in the reference. This uncertainty varies greatly between the various references, as the different authors have used different methods to account for both the observational and systematic uncertainties for their sources, which vary in flux and exposure times. While these uncertainties may bias our fit, the close correlation observed and the varying sizes of the samples (both discussed in the next section) will tend to minimize these effects. The given line uncertainties in the references were carried over when calculating their corresponding ratios.

The majority of objects within our sample were observed with the Spitzer IRS, with the remainder coming from ISO SWS observations (as noted in Table 1). In the cases where objects were observed twice (for example with both Spitzer and ISO), we have included both observations, to indicate the systematic uncertainty in the sample. For all of our sample, all four MIR lines fall within Spitzer’s IRS short-high (SH) module (9.9-19.6\,$\mu$m) and ISO’s SWS (2.38 to 45.2\,$\mu$m), meaning that aperture effects are limited to that due to the different wavelengths of the lines in the ratios (a factor of 1.2 for \([\text{S}\,\text{iv}]/\text{[Ne}\,\text{ii}]\) and \([\text{Ne}\,\text{ii}]/\text{[Ne}\,\text{iii}]\)

Within our total sample there are approximately 8 objects observed by both telescopes, and a similar number of objects observed by Spitzer whose lines have been extracted by two different authors using different methods. For objects by both telescopes (e.g. NGC 4151), the difference in line ratios is of the order of 0.3 dex, most likely due to the different telescope apertures and pointings. Some objects were observed once by ISO, but have multiple pointings by Spitzer-IRS (e.g. M82), and for these objects we consider the ISO observation an integrated flux and the IRS observations to be individual H\,\text{n} regions. For the few IRS observed objects investigated by different authors, the differences in line ratios arise purely due to the different line flux extraction techniques (e.g. H2Zw40) and are of the order of 0.2 dex, and within the given uncertainties. However the small number of objects observed multiply (∼15, distributed across both AGN and Starburst/BCD) compared to the total sample size (355), mean that a bias of the final fit towards these types of objects will not occur.

In extracting our sample we excluded all objects in which any of the four lines were undetected, or for which only upper limits were provided. This means that we do have a bias in the sample against weak line objects, but, with objects covering a broad range of distances and four orders of magnitude in line ratio, this bias is likely to be weak. This bias is present, however, in at least one of the groups (ULIRGs), and is discussed further in the next section.

The total sample represents a large variety in ionising conditions (∼2.1 < log([Ne\,\text{ii}]/[Ne\,\text{iii}] < 1.8), metal abundances (ranging from log(O/H) + 12 ≈ 7.1 (SBS 0335-052W) to ≈ 8.8 (IC342)) and the object particulars such as infrared luminosities (PNe to ULIRGs), galaxy types (blue compact dwarf galaxies to massive ULIRGs), and star formation rates (BCDs and H\,\text{n} regions of less than a few \(M_\odot\) yr\(^{-1}\) to ULIRGs \(\sim 100\)‘s \(M_\odot\) yr\(^{-1}\)).

3 RESULTS & DISCUSSION

The final sample of 355 emission-line objects is presented in figure 1 in the form of two emission line diagnostic diagrams: \([\text{S}\,\text{iv}]/\text{[Ne}\,\text{ii}]\) vs \([\text{Ne}\,\text{ii}]/\text{[Ne}\,\text{iii}]\) (figure 1A) and \([\text{S}\,\text{iv}]/\text{[Ne}\,\text{ii}]\) vs \([\text{Ne}\,\text{ii}]/\text{[Ne}\,\text{iii}]\) (figure 1B). The separate classes of object within the sample are differentiated both by colour and shape, as labelled in the key in the upper left hand corner of the diagrams. In the lower right corner of the diagrams we show the average observational uncertainty across the sample, as given within the references. As noted previously, the uncertainty given in the references varies significantly between the different classes, ranging from ∼1% for M33 & M83 to ∼40% for the galactic H\,\text{n} regions. In all classes however, the uncertainty on the \([\text{Ne}\,\text{ii}]/\text{[Ne}\,\text{iii}]\) ratio is lower than that of the other two ratios considered here, partly due to the strength of the neon lines (higher signal-to-noise), but mostly due to the location of the \([\text{S}\,\text{iv}]/\text{[Ne}\,\text{iii}]\) in the silicate absorption feature (discussed further below), which both decreases the strength of this line and adds an additional uncertainty due to extinction. In any case, these uncertainties are applied to the reduced \(\chi^2\) fit discussed below.
Figure 1. Mid-IR line ratio diagrams revealing the correlation between \([\text{Ne}\text{III}]/\text{[Ne}\text{II}]/\text{[Ne}\text{III}]\) and \([\text{Ne}\text{III}]/\text{[Ne}\text{II}]/\text{[Ne}\text{III}]\) line ratios. The lower diagram also shows our best fit to the ratios (solid line) along with the 1-σ dispersion (dotted lines), as given in Table 2.

Table 2. Fit parameters for the full sample and individual classes, including the number of objects (N) within the sample.

| Object class     | N  | α    | β    | σ_{\text{xy}} |
|------------------|----|------|------|---------------|
| Full sample      | 355 | 0.81 | 0.36 | 0.25          |
| H\text{\textsc{ii}} regions | 65  | 0.74 | 0.42 | 0.23          |
| Extragalactic H\text{\textsc{ii}} | 97  | 0.82 | 0.36 | 0.15          |
| ULIRGs            | 20  | 0.49 | 0.26 | 0.33          |
| AGN               | 20  | 0.69 | 0.29 | 0.25          |
| PNe               | 20  | 0.74 | 0.56 | 0.30          |
| Starburst         | 56  | 0.65 | 0.32 | 0.28          |
| BCDs              | 49  | 0.86 | 0.32 | 0.30          |

In both diagrams we plot a vector that indicates the effects of an \(A_V = 30\) magnitudes of extinction on the ratios for an \(A_V = 30\) magnitudes. The lower diagram also shows our best fit to the ratios (solid line) along with the 1-σ dispersion (dotted lines), as given in Table 2.

The first diagram, figure 1a, reveals the standard space-based empirical relationship, just as many of the AGN classified galaxies also have strong, active star formation. In figure 1b, we show the ground-accessible ratio \([\text{S}\text{IV}]/\text{[Ne}\text{II}]/\text{[Ne}\text{III}]\) versus \([\text{Ne}\text{III}]/\text{[Ne}\text{II}]/\text{[Ne}\text{III}]\) ratio when unavailable. Compared with figure 1a, the data show surprisingly less scatter. This probably arises due to the use of a common denominator \([\text{Ne}\text{II}]/\text{[Ne}\text{III}]\), but the \([\text{Ne}\text{II}]/\text{[Ne}\text{III}]\) line may also be introducing some scatter into figure 1a, possibly due to its longer wavelength (and hence lower resolution).

To quantify this correlation we perform a linear least-squares fit to the full sample using the IDL routine FITEXY, giving the empirical relationship,

\[
\log (\text{[Ne}\text{III}]/\text{[Ne}\text{II}]) = \alpha \log ([\text{S}\text{IV}]/[\text{Ne}\text{II}]) + \beta. \tag{1}
\]

The result of this fit, along with the 1 σ dispersion, is given in Table 2.

The first thing to note is that the log-space linear fit to the full sample appears to be accurate to 0.25 dex (that is, less than a factor of ~2 in the linear ratio) over four orders of magnitude in the ratio, demonstrating the ability of ground-based IR spectrographs to do ionization studies of nebulae. The dispersion around this relation is greater than the average uncertainty, indi-
cating either inaccurate uncertainties, intrinsic variations due to the
variety of sources or, most likely, a combination of both.

In addition to the full fit we also present fits to our various ob-
ject classes, also presented in Table 2. Overall, the relations match
reasonably well with the full sample fit, with the two major out-
liers either side being the planetary nebulae (high offset in $\beta$) and
the ULIRGs (shallow slope in $\alpha$). These individual fits can be used
when the specific class of objects being observed are known, but
we suggest that the full fit should be used in most circumstances,
as it is a more robust fit and includes all object classes.

In figure 1, the PNe are visibly offset from the rest of the
sample, both to high $[S iv]/[Ne ii]$ and higher than average
$[Ne iii]/[Ne ii]$. This offset is most likely due to the hotter and harder
white dwarf ionizing source in PNe, although this then poses the
question why the AGN, which also have a harder ionizing spec-
trum than that found in H II regions and galaxies, is not also more
offset.

The shallow slope of the ULIRGs sample demonstrates one of
the issues with the $[S iv]/[Ne ii]$ ratio: the location of the $[S iv]_{10.5\mu m}$
in the $9.7\mu m$ silicate absorption feature. Of the Farrah et al. (2007)
sample of 53 ULIRGs over half have no detections or upper limits
for the $[S iv]$ line, while a large fraction of those which do have
detections are uncertain, with detections of less than 3 sigma. As
noted in the paper, only in ULIRGs with low silicate depths ($S_{\alpha} \lesssim
2.1$) is the $[S iv]$ feature detected, even when the $[Ne iii]_{3.8\mu m}$ line is
present. Thus there is likely both a bias in our ULIRG sample
and an offset, such that low $[S iv]/[Ne ii]$ ULIRGs are also those
with high extinction and therefore offset from the relation, while
the highest extinction sources are not included at all.

Another spectral feature which may affect the line ratio rela-
tion is the $12.7\mu m$ PAH feature seen clearly in many galaxy spectra
(Smith et al. 2007). This broad feature lies below the $[Ne ii]$ line,
and makes the determination and subtraction of the underlying con-
tinuum difficult, and thus increases the uncertainty in the flux of
this line. As mentioned before, this may explain the offset seen in the
Engelbracht et al. (2008) sample.

However, even with these outliers the correlation is surpris-
ingly tight. Simple photoionization theory expects such a correla-
tion, with higher ionization leading to higher values for both ratios
(Deo & Sutherland 2003), but variations in the ionization param-
meter and ionizing spectrum cause different changes in the two ra-
tios. Such variations have been explored in the case of starbursts
and H II regions in Thornley et al. (2000) and Rubin et al. (2008)
and, given these results, the tight fit indicates a close correlation
between ionization parameter and spectral hardness in these ob-
jects.

One further issue is abundance variations. The $[Ne iii]/[Ne ii]$ ratio
is sensitive to abundance variations only indirectly, through the
resulting temperature effects. The $[S iv]/[Ne ii]$ ratio however,
can be directly affected by variations between the sulphur and neon
abundances. As both are primary elements, significant total abun-
dance variations are not expected. However, depletion of sulphur
onto dust may cause variations in the gas phase and hence in the
emission lines. While the total depletion of sulphur onto dust is un-
certain (though see Lebouteiller et al. 2008), it does not seem to be
a great effect on the Ne/S ratio, as shown by Rubin et al. (2007, 2008),
and therefore on the $[S iv]/[Ne ii]$ ratio.

Thus, in summary, to determine whether it is reasonable to
use the ground-accessible ratio $[S iv]_{10.5\mu m}/[Ne ii]_{2.8\mu m}$ as a replace-
ment for the diagnostic $[Ne iii]/[Ne ii]$ ratio, we have collated exist-
ing ISO and Spitzer spectral observations of a wide range of astrophysical objects from the literature. We find a good correlation
between these ratios with a linear fit giving the relation,
\[
\log ([Ne iii]/[Ne ii]) = 0.81 \log ([S iv]/[Ne ii]) + 0.36,
\]
with a 1 $\sigma$ dispersion of 0.25, corresponding to an uncertainty in the
estimated line ratio of $\sim 70\%$. We propose that for future ground
based observations this relationship be used to determine the ion-
zation state of the observed objects, though note that caution must
be applied when looking at heavily extinguished ($A_v \geq 20$) objects
where the $[S iv]_{10.5\mu m}$ may be affected by the $9.7\mu m$ silicate absorp-
tion feature.

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1 The ionization parameter is a measure of the ionizing photon density over
the gas density; $U = Q_{ion}/n_0 c$, where $Q_{ion} = \int E_{ion} F(E) d\nu$.
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