Ultraviolet Lines and Gas Composition in NGC 1068

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ABSTRACT

Recent ultraviolet and X-ray observations suggest that the Fe/O ratio in the NLR gas in NGC 1068 is abnormally high. The X-ray analysis, which is presented elsewhere, suggests a large Fe/H and the data shown and discussed here, in particular the extremely weak O\textsc{iii}] λ1663 line, argue for small O/N and O/C. Models to support this claim are shown and discussed. They include improved reddening estimates, dusty and dust-free calculations, and a range of abundances. The anomalous composition makes NGC 1068 unique among Seyfert galaxies and an unusual laboratory for investigating metal enrichment and depletion.

1. Introduction

NGC 1068 is perhaps the ideal benchmark for studying gas composition in active galaxies. Its proximity, high luminosity and inclination make spectroscopic studies easier than in most known Seyferts. As a result, the available spectroscopic information is of unusual quality and coverage. The optical and UV spectrum have been studied in numerous papers (Snijders, Netzer & Boksenber; 1986, and references therein) and the extreme UV spectrum has been observed by HUT (Kriss et al. 1992 and this volume). Dozens of emission lines have been measured and soon to be published papers will include the first attempt at high spatial resolution long-slit spectroscopy. This will provide line ratios in regions of different levels of ionization and will enable a meaningful comparison with multi-component models.

The X-ray information on this source is even more remarkable. BBXRT (Marshall et al. 1993) and ASCA (Ueno et al. 1994) observations revealed the presence of several strong X-ray lines. The iron Kα complex is clearly split into three components (Marshall et al. 1993), suggesting the presence of highly ionized X-ray heated gas. There is also evidence for several soft X-ray lines with equivalent width of at least 50–100 eV. This is the first and

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best evidence for soft X-ray lines in any AGN. The analysis of the X-ray lines can be used to put limits on the Fe/O abundance ratio. The complimentary information from UV studies provides limits on O/N and O/C.

This paper discusses the gas composition in NGC 1068. The X-ray aspects are reviewed in §2. A detailed analysis of the UV spectrum is given in §3 with emphasis on recent HST and HUT observations. §4 summarizes the most important findings of this work.

2. The X-ray spectrum of NGC 1068

The most detailed X-ray investigations of NGC 1068 are by Marshall et al. (1993) and Ueno et al. (1994). Previous Ginga observations are described by Awaki et al. (1990) and ROSAT imaging is described in Wilson et al. (1992). The analysis of the BBXRT data, by Marshall et al. (1993), suggests two different components that contribute to the iron Kα complex. 1. A “warm” component, with a temperature of about $2 \times 10^5$ K, which produces the 6.4 keV line. This gas is photoionized by the nuclear source and is also the “mirror” reflecting the optical-UV continuum and the broad Balmer lines. 2. A hot, $T \simeq 4 \times 10^6$ K component, producing the Fe xxi 6.7 keV and Fe xxi 6.96 keV lines. According to Marshall et al., the two contributions about equally to the scattered 6.4 continuum. A different combination of components is suggested by Iwasawa et al. (1997). In their scheme, the 6.4 keV line is due to a Compton thick gas, with very large column density, presumably the thick walls of the central torus. Iwasawa et al. suggested also a second, hot component to explain the highly ionized iron lines. In their model, the scattered 6.4 keV continuum is mostly due to the Compton-thick gas and there is no explanation of the “mirror”.

Marshall et al. (1993) reported an upper limit on the O viii 653 eV line which indicates a large oxygen under abundance. The most significant comparison is with iron since the observed Kα lines enables a simple determination of Fe/H. The analysis suggests an iron over abundance, relative to solar, by a factor of 2–3 and oxygen under abundance by a factor of 3–5. Ueno et al. (1994) confirmed the upper limit on the O viii 653 eV line and the BBXRT measurements of the Kα lines. They assumed that most of the soft X-ray flux is from hot, collisionally excited plasma, in which all metals are highly depleted. Netzer and Turner (1997) reanalyzed the ASCA data. They measured several soft X-ray lines, such as Ne ix 915 eV, Ne x 1.02 keV, H-like and helium like lines of magnesium, silicon, sulphur and argon, and several Fe-L lines, and confirmed the two-component model. Marshall et al. (1993) have also examined the UV spectrum of NGC 1068 and suggested more evidence for the small O/H.
3. The Ultraviolet Spectrum and the O/N abundance

The observed optical -UV spectrum of NGC 1068 is described in Snijders et al. (1986). More recent, shorter wavelength (900–1800 Å) observations by HUT are reported in Kriss et al. (1992; see also G. Kriss contribution in this volume). All large aperture data represent the spectrum over a region of roughly 20 arc-sec in diameter. The high resolution HST imaging, such as the one presented in this meeting (e.g. Z. Tsvetanov contribution), clearly emphasize the limitation of large aperture observations.

The HST archive contains some high spatial resolution spectroscopy of this galaxy. We have used one such unpublished data set, obtained by centering on an off-nucleus cloud, to try and separate the high and the low excitation lines. Our line list (Table 1) is an average of several sources designed to represent an average ionization cloud.

3.1. Dust and Reddening

The spectrum of NGC 1068 indicates a substantial amount of reddening. Snijders et al. (1986) used a galactic type extinction and estimated $E_{B-V} = 0.4$ mag., mostly from the He II $\lambda 4686$/He II $\lambda 1640$ line ratio. The more recent HUT observations of Kriss et al. (1992) discovered two helium lines, He II $\lambda 1640$ and He II $\lambda 1085$. Their ratio, relative to He II $\lambda 4686$, is inconsistent with a single extinction law. This has been discussed, extensively, by Kriss et al. (1992) and Ferguson et al. (1995). Ferguson et al. (1995) suggested a double reddening correction approach in which all lines with wavelength longer than 1640 Å were corrected with one extinction curve and all lines with shorter wavelength were corrected with a different curve. Unfortunately, there was a mistake in applying this procedure to the data (Ferguson, private communication) and the reddening corrected line intensities in their table 1 are erroneous.

The difficulty encountered by Kriss et al. (1992) and Ferguson et al. (1995) is due to the inconsistency in the observed flux of three HeII lines at 4686, 1640 and 1084 Å. The line intensities are predicted by simple recombination theory and are very reliable reddening indicators. Ferguson et al. noted that continuum fluorescence (the absorption of continuum photons by resonance lines) can contribute significantly to several of the observed UV transitions. They have shown that the C III $\lambda 977$ and N III $\lambda 990$ intensities can considerably increase due to this process. Our new calculations support this claim. They also show that N II $\lambda 1084$ is significantly affected by this process. When including continuum fluorescence in the calculations of this line, with velocity broadening of 500 km s$^{-1}$, we find that this can explain up to 50% of the observed 1084 Å flux. This cures the reddening anomaly and
enables a single, self consistent reddening solution with a galactic-type extinction. We further note that some other lines can significantly be affected by continuum fluorescence. In particular, in large column density situations, there can be a large contribution at 1304Å, 1039Å, 1026Å, 990Å, 976Å, and 972Å, from OI resonance lines. Some of the observed flux at around 1035Å, 977Å and 990Å, can be due to this process, although the absence of a strong 1304Å is problematic. Examples are shown in Table 1.

Table 1 lists dereddened line ratios assuming galactic-type extinction and $E_{B-V} = 35$ mag. The calculated contributions to the 1084Å feature, suggests this to be the most reliable reddening estimate. The listed uncertainties on the dereddened line intensities represent the 2σ intervals, as given in the original papers, without taking into account the uncertainty in reddening. The listed intensity of Lyα has no assigned uncertainty due to the blending under geocoronal Lyα.

### 3.2. Photoionization Calculations

We have used the photoionization code ION (Netzer 1996 and references therein) to carry out extensive photoionization modeling of the NLR gas in NGC 1068. We have assumed various densities and column densities, different geometries and dust distribution and allowed for abundance variations. The line list presented in Table 1 is used for comparison and we have tried splitting it into high and low excitation lines to test the quality of the fit. Two single component models are shown in the table. They have similar ionization parameter, density and column density, and differ by the assume amount of internal dust. The assumed turbulent velocity is 500 km s$^{-1}$.

The continuum used for the calculation is similar to the one used by Marshall et al. (1993), except for the soft X-ray part. It is made of a broken power-law with typical optical-UV slope and $\alpha_{ox}=1.35$. This fits best with the overall energy budget as well as the observed hard X-ray flux. The main uncertainty is due to the shape of the unobserved UV bump. As argued by Wilson et al. (1992), there is a likely strong soft-X-ray contribution from an extended source, presumably a starburst region. This implies a weaker soft X-ray central source, compared with the one used in Marshall et al.. We have considered this possibility and have assumed a hard ($F_\nu \propto \nu^{-0.5}$) X-ray continuum extending from 1 to 50 keV, normalized to the observed flux at 6.4 keV. The 1 keV point was connected to the lower energy continuum used by Marshall et al..

In anticipation of the unusual composition, and in accord with the X-ray analysis, we have modeled the NLR gas with He/H=0.1 and the following dust-free composition:
Table 1: Observed and calculated line intensities

| Line     | Dusty NLR | Dust-free NLR | Dereddened line ratios |
|----------|-----------|---------------|------------------------|
| Hα       | 3.3       | 2.75          | 2.7-3.0                |
| Hβ       | 1.68      | 1.90          | 4.1 - 4.8              |
| Lyα      | 0.25      | 0.29          | 1.2 - 2.1              |
| He II λ4686 | 0.42    | 0.30          | 0.46 - 0.72            |
| He II λ1640 | 1.68     | 1.90          | 4.1 - 4.8              |
| He II λ1085 | 0.25     | 0.29          | 1.2 - 2.1              |
| C II λ1335 | 0.18     | 0.61          | 0.7 - 1.1              |
| C III λ977  | 0.77     | 1.5           | 3.4 - 4.7              |
| C III λ1909 | 5.3      | 6.6           | 4.9 - 6.0              |
| C IV λ1549  | 6.8      | 9.8           | 7.2 - 8.3              |
| N II λ1084  | 0.13     | 0.39          | 1.2 - 2.1              |
| N III λ990  | 0.43      | 0.80          | 1.5 - 2.5              |
| N III λ1750 | 0.93     | 0.48          | 0.7 - 1.4              |
| N IV λ1486  | 1.22     | 0.53          | 0.8 - 1.4              |
| N V λ1240   | 1.1       | 0.63          | 8.4 - 10.1             |
| [O II] λ3727 | 0.24    | 0.12          | 0.5 - 0.8              |
| [O III] λ5007 | 12.0    | 9.8           | 16 - 18                |
| O III λ1663 | 0.46     | 0.30          | <0.29                  |
| O IV λ1402+Si IV λ1397 | 1.29 | 0.84         | 1.6 - 2.2              |
| O VI λ1035  | 0.22      | 0.19          | 16 - 20                |
| O Iλ1304    | 0.09      | 0.26          |                       |
| O Iλ1026    | 0.03      | 0.20          |                       |
| O Iλ1039    | 0.02      | 0.13          |                       |
| O Iλ989     | 0.04      | 0.31          |                       |
| O Iλ976 + 972 | 0.01 | 0.26         |                       |
| Mg II λ2798 | 1.8       | 3.7           | 0.7 - 1.1              |

* Galactic dust-to-gas ratio. Ionization parameter of 9.4×10^{-3} and n_H=10^4 cm^{-3}.

* E_B−V = 0.35. The Observed Hβ flux is 1.6×10^{-12} ergs s^{-1} cm^{-2}

* blended with N II λ1084, see text
H:C:N:O:Ne:Mg:Si:S:Ar:Fe = 10^4:3:1:1.5:1:0.33:0.33:0.16:0.07:1.2.

For the dusty NLR we have assumed gas phase composition of
H:C:N:O:Ne:Mg:Si:S:Ar:Fe = 10^4:1.6:1:1.5:0.6:0.16:0.016:0.054:0.016:0.016.

Imaging of NGC 1068, through various narrow band filters, clearly show ionization stratification. Thus single component models, like the ones shown in the table, with “mean” properties, are poor representations of the more complex physical situation. The emphasis in this work is on the gas composition, and we do not list most of the calculated models. We also point out that the derived E_{B-V} is more appropriate to the high ionization component, since it is based on HeII line ratios. Any composite model must take into account the possibility that the high and the low ionization lines are affected in a different way by internal dust. In particular, internal dust is more important in high ionization parameter environment (e.g. Laor and Netzer, 1993). For example, in dusty models with much larger ionization parameter, the HeII line ratio is affected too. However, the derived O/N and O/C abundance ratios (see below) are hardly affected.

### 3.3. Abundance determination

A key issue in the present study is the abundance of iron and oxygen. The iron abundance can be obtained from X-ray modeling since the equivalent width of the strong Kα lines is a direct measure of Fe/H. The oxygen abundance can be determined by comparing oxygen, nitrogen and carbon emission lines. As argued by Shields (1976), several ultraviolet semi-forbidden lines can be used in this analysis because of their similar excitation and level of ionization. The line ratios most suitable for our purpose are O III] λ1663/N III] λ1750 and O III] λ1663/C III] λ1909.

The ionization structure of a gas cloud exposed to a typical AGN ionizing continuum shows a large overlap of the C+2, N+2 and O+2 ionization regions. This is illustrated in Fig. 1 for the assumed NGC 1068 continuum. Given the similar ionization structure, we can use the observed line ratios, to deduce relative abundances. The theoretical ratios are

\[
\frac{I(\text{OIII}\lambda1663)}{I(\text{NIII}\lambda1750)} = 0.41T_4^{-0.04}\exp(-0.43/T_4)\frac{N(O^{+2})}{N(N^{+2})}
\]

and

\[
\frac{I(\text{OIII}\lambda1663)}{I(\text{CIII}\lambda1909)} = 0.15T_4^{0.06}\exp(-1.11/T_4)\frac{N(O^{+2})}{N(C^{+2})}
\]

where T_4 is the temperature in units of 10^4 K. We further assume (Fig. 1) that N(O)/N(N) \simeq N(O^{+2})/N(N^{+2}) and N(O)/N(C) \simeq N(O^{+2})/N(C^{+2}). The observed
Fig. 1.— Ionization structure for dusty and dust-free models calculated for NGC 1068. Note the almost perfect overlap of the C$^{+2}$, N$^{+2}$ and O$^{+2}$ zones.
intensities (Table 1), combined with a typical $T_4=1.5$, gives $N(O)/N(N)\leq 1.0$ and and $N(O)/N(C)\leq 0.73$. These ratios are much below the solar values and confirm the large oxygen under abundance in this source. Metal depletion on grains cannot provide an explanation to this ratio unless the gas and dust composition are vastly different from their ISM values.

4. Discussion and Conclusions

Analysis of the composite spectrum of NGC 1068 clearly demonstrates the unusual oxygen line ratios. The examples shown in this work suggest that the NLR gas has extremely low oxygen abundance. The models listed in Table 1 are not intended to represent the full physical conditions, only to demonstrate the more important processes. They confirm the need for large turbulent motions (Ferguson et al.; 1995) and eliminate much of the problem raised by Kriss et al. regarding the intensity of C$\text{III}$ $\lambda 977$ and N$\text{III}$ $\lambda 990$. They fall short of explaining the strong O$\text{VI}$ $\lambda 1035$ and N$\text{V}$ $\lambda 1240$ lines and suggest that higher ionization components, perhaps of optically thin gas, may be important. In summary, future models of NGC 1068 must take into account the following:

1. The ionized gas is stratified and regions of different excitation must be combined in order to mimic the observed large aperture spectrum.

2. Large turbulent motions make continuum fluorescence an important process and can significantly increases the intensity of various resonance lines. This helps to explain the strong C$\text{III}$ $\lambda 977$ and N$\text{III}$ $\lambda 990$ lines (Ferguson et al.; 1995), the anomalous 1084Å feature (this work) and perhaps the strength of some ultraviolet OI lines (this work). The process is likely to be more important in Seyfert 2s, where the central continuum is obscured from direct view.

3. When taking into account the N$\text{II}$ $\lambda 1084$ line, there is a good agreement with a single galactic-type extinction law, with $E_{B-V} \simeq 0.35$ mag.

4. Dust mixed with the NLR gas is likely to be important in the NLR.

5. The absence of the O$\text{III}$] $\lambda 1663$ line suggests oxygen under abundance, compared with nitrogen and carbon. This is in line with indications from X-ray (Netzer and Turner; 1997) and millimeter (Sternberg, Genzel & Tacconi; 1994) observations. It is interesting to note the intensity of this line in other Seyfert galaxies. O$\text{III}$] $\lambda 1663$ is clearly observed in both NGC 4151 (Ulrich et al. 1985) and NGC 5548 (Crenshaw et al. 1993) during times when the broad emission lines are weak. The line is also
observed in the Seyfert 2 galaxy NGC 5525 (Tsvetanov et al., in preparation) where it is stronger than N\textsc{iii}] \lambda 1750. In all these cases, there are indications for solar O/C and O/N. Finally, our recent HST study of the Seyfert 2 galaxy NGC 3393 (Cooke et al.; 1997) does not show the O\textsc{iii}] \lambda 1663 line. However, the FOS spectrum is of moderate quality and the observed intensity is consistent with solar O/C and O/N.

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