The Seyfert 1 Galaxy Mrk 335 at a very low flux state: mapping the soft X-ray photoionised gas

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Received 9 January 2008 / Accepted 7 March 2008

ABSTRACT

Context. This paper reports on an XMM-Newton observation of the Seyfert 1 Galaxy Mrk 335 performed as a target of opportunity when the source was in an unusually low flux state.

Aims. The low level of continuum emission unveiled an underlying line-rich soft X-ray spectrum, which can be studied with the Reflection Grating Spectrometer.

Methods. The emission features were analysed at high resolution with unprecedented detail for this source. Line ratio diagnostics from H-like and He-like ions indicate that the line emission arises in X-ray photoionised plasma. Extensive simulations were performed with the CLOUDY photoionisation code. The physical properties of the line emitting material were derived from the comparison of the expected and observed line intensities.

Results. Because of the degeneracy in the ionisation parameter, a number of different solutions for the electron density and column density of the gas are consistent with the spectral diagnostics. This prevents us from uniquely determining the properties of the plasma; however, the location(s) of the X-ray photoionised gas can be constrained to within 0.06 pc (outer boundary). This limit places the X-ray line emitting gas at the inner edge of the material where the broad optical lines are produced (broad line region).

Key words. galaxies: active – galaxies: individual: Mrk 335 – X-rays: galaxies

1. Introduction

The soft X-ray spectrum of Seyfert galaxies has represented for astronomers a region of great interest and, at the same time, a sort of challenge. With the advent of high-resolution spectrometers onboard XMM-Newton and Chandra, it has been possible to reveal the nature of emission in this spectral band at least in obscured sources (Guainazzi & Bianchi 2007, and references therein). Many authors concur to indicate that the origin of the soft X-ray emission in these sources is caused by photoionisation of extended circumnuclear gas on kpc scale irradiated by the active nucleus which produces He and H-like transitions of heavy elements and L-shell transitions from Fe (e.g. NGC 1068, Kinkhabwala et al. 2002; Mrk 3, Bianchi et al. 2005, NGC 4151, Armentrout et al. 2007, to cite the most outstanding cases).

On the other hand, the scenario for unobscured AGN is not so definite. The lack of line-of-sight obscuring material in this type of sources, allows the whole nuclear radiation to escape unblocked to the observer, so that the soft X-ray spectrum is dominated by a smooth excess of continuum rather than features from reprocessed material (Piconcelli et al. 2005; Crummy et al. 2006).

In about half of the Seyfert 1 galaxies (Crenshaw et al. 2003; Blustin et al. 2005), the presence of intervening ionised gas is directly observable as a series of absorption features, which present velocity shifts when originating in outflowing or inflowing gas. For the sources studied with the longest integration times, it has been possible to place some constraints on the electron density of the gas and, consequently, on the distance of these warm absorbers, mainly through variability studies. The emerging picture is far from being a homogeneous description of the circumnuclear ionised gas. Among many cases, we recall that the distance of the absorber(s) in NGC 3783 was estimated to be 1–3 pc from the nucleus (Netzer et al. 2003; Behar et al. 2003), whereas it was found to be consistent with subparsec scale in NGC 3516 (Netzer et al. 2002) and it was estimated to be within 4 light days from the nucleus in NGC 4051 (Krongold et al. 2007).

Mrk 335 is a Seyfert 1 galaxy (z = 0.026) with a long X-ray history, since it has been observed by almost all X-ray observatories in the past. EXOSAT (Turner & Pounds 1989) and BBXRT (Turner et al. 1993a) revealed the presence of an excess of emission in the soft X-rays band, later confirmed in ASCA data by Reynolds (1997). No clear evidence of warm absorption was established (Reynolds 1997; George et al. 1998), but ROSAT data tentatively suggested spectral complexity in the soft X-ray (Turner et al. 1993b). Nandra & Pounds (1994) found evidence of a hard X-ray edge in the Ginga data. The presence of the Compton reflection component and a strong Fe Kα line was revealed in BeppoSAX data (Bianchi et al. 2001) and later confirmed in XMM-Newton observations (Gondoin et al. 2002; Longinotti et al. 2007; O’Neill et al. 2007). In 2006 the source was observed by the Suzaku satellite (Larsson et al. 2007). The spectrum was characterised by a strong soft excess and a reflection component, closely resembling the XMM-Newton data; but despite the availability of the high-energy data up to 40 keV, it has not been possible to model the broadband spectrum unambiguously. In May 2007, Swift caught Mrk 335 in a historical low X-ray flux state, with an extremely hard X-ray power law above 2 keV (Grupe et al. 2007). Following this discovery, the source was observed again by XMM-Newton in July 2007 as a target...
Table 1. Observation Log of Mrk 335 as observed by XMM-Newton.

| OBSID            | Date (dd/mm/yyyy) | RGS exp (ks) | pn exp (ks) | T_{soft} (10^{-12} erg cm^{-2} s^{-1}) | T_{hard} (10^{-12} erg cm^{-2} s^{-1}) | Flux_{0.3-2} (10^{-12} erg cm^{-2} s^{-1}) | Flux_{2-10} (10^{-12} erg cm^{-2} s^{-1}) |
|------------------|-------------------|--------------|-------------|---------------------------------------|---------------------------------------|-------------------------------------------|-------------------------------------------|
| 0510010701a      | 10/07/2007        | 22           | 15          | 2.84 ± 0.03                           | 1.95 ± 0.04                           | 1.02 ± 0.07                               | 3.34 ± 0.23                               |
| 03068701b        | 03/01/2006        | 130          | 92          | 2.72 ± 0.01                           | 32.16 ± 0.04                          | 2.09 ± 0.01                               | 17.72 ± 0.07                              |
| 0101040101c      | 25/12/2000        | 34           | 30          | 2.80 ± 0.01                           | 31.74 ± 0.06                          | 2.16 ± 0.02                               | 15.00 ± 0.02                              |

a Grupe et al. (2008), b O’Neill et al. (2007), c Longinotti et al. (2007). The X-ray properties have been measured from the pn spectra.

2. Observation and data reduction

Mrk 335 was observed by XMM-Newton on 10 July 2007 (OBSID 0510010701) for a duration time of 25 ks. Data from the three instruments EPIC (0.3–10 keV), RGS (5–38 Å), and Optical Monitor (OM, 6 filters in the 1800–6000 Å bandpass) were available (Struder et al. 2001; Den Herder et al. 2001; Mason et al. 2001). The detailed analysis of EPIC and OM data will be published in Grupe et al. (2008). In this paper, only the RGS data from the ToO observation are considered. However, Table 1 reports the broadband properties from all the three XMM-Newton available data sets to allow the reader an immediate comparison among the flux states of this source.

For the background and response matrices, no background flares due to high-energy particles are present in this observation. For the OM data, we decided to extract the magnitudes and fluxes from the pipeline products (PPS).

3. RGS spectral analysis

The spectral analysis was performed using the fitting package SPEX (ver. 2.0), simultaneously fitting both spectra from the two RGS cameras. A preliminary analysis was carried out using the first-order spectra, re-binned according to the resolution of the instrument and with a signal-to-noise ratio of 5 over the whole 5–38 Å range. This binning was used only to test the agreement between the power-law slopes of the RGS and of the EPIC data and to visually check for the presence of broad features in the spectrum (Fig. 1). Otherwise, since many spectral channels fall in the limit of low number of photons, the unbinned spectrum was used for the spectral analysis and the C statistic was applied (Cash 1979). The quoted errors correspond to the 1σ level (i.e. ΔC = 1, for one interesting parameter). Galactic absorption of column density N_{HI} = 3.9 × 10^{20} cm^{-2} is included in all the models (Dickey & Lockman 1990).

3.1. A close look at the H-like and He-like emission lines in the spectrum

The spectral fit in the previous section and the fluxes reported in Table 2 reveal that the OVII triplet is characterised by dominant or equal to ΔC ≈ 4, corresponding to 95.4% for one free parameter. The final fit statistic including all transitions in Table 2 is C-statistic = 6247 for 5264 degrees of freedom (d.o.f.). As a second step, we checked for the presence of the radiative recombination continua (RRC) from CV, NVII, OVII, and OVIII at λ = 31 622, 18 587, 16 771, and 14 228 Å, which are visible in the binned spectrum. They were incorporated in the model, but when this is fitted, only upper limits on the emission measures could be found, so they are not considered in the following. A careful visual inspection of the spectrum did not reveal any absorption feature.

The detected lines were then checked for line broadening. The OVIII Lyα line is the most intense isolated transition in the spectrum, and it is not affected by bad pixels. A Gaussian profile was fitted to this line with the wavelength frozen to the expected value of 18.96 Å and the width free to vary. The measured line FWHM is σ = 0.14 ± 0.05 Å. We fitted all the spectral lines fixing their FWHM to the value corresponding to the one of the OVIII Lyα, obtaining the fluxes reported in the third column of Table 2. The spectrum was also checked for line shifts by leaving the centroids of the strongest transitions free to vary. For the OVIII Lyα line, a blueshift of Δλ ≈ −0.018 ± 0.013 Å is found, with an improvement of ΔC = 7. For the OVII intercombination line the 90% limits on the shift with respect to the laboratory wavelength are +0.018 and −0.054 Å. Taking into account that the present signal-to-noise ratio does not allow us to distinguish line contamination and that the RGS systematic error of 8 mÅ is included in the error estimate, we conclude that the peak wavelengths are consistent with the laboratory values.

http://www.sron.nl/divisions/hea/spex/version2.0/release/index.html

Table 2. Fluxes of the soft X-ray lines found in the RGS spectrum.

| Transition   | λ (Å) | Flux_{FWHM=0} (ph m^{-2} s^{-1}) | ΔC | Flux_{FWHM=OVIII} (ph m^{-2} s^{-1}) |
|--------------|-------|---------------------------------|----|-------------------------------------|
| FeXVII       | 17.017| <0.05                           | ΔC = 1 | 0.06 ± 0.04                       |
| OVII Heβ     | 18.627| <0.03                           | ΔC = 0 | 0.06 ± 0.04                       |
| OVIII Lyα    | 18.969| 0.20 ± 0.04                     | ΔC = 31 | 0.27 ± 0.05                       |
| OVII Heα (r) | 21.600| 0.10 ± 0.06                     | ΔC = 4 | 0.17 ± 0.08                       |
| OVII Heα (i) | 21.790| 0.26 ± 0.08                     | ΔC = 21 | 0.31 ± 0.09                       |
| OVII Heα (f) | 22.101| 0.17 ± 0.07                     | ΔC = 12 | 0.16 ± 0.07                       |
| NVII Lyα     | 24.781| 0.13 ± 0.05                     | ΔC = 12 | 0.18 ± 0.05                       |
| CVI Lyβ      | 28.446| 0.13 ± 0.06                     | ΔC = 13 | 0.20 ± 0.07                       |
| CVI Lyα      | 33.336| 0.15 ± 0.06                     | ΔC = 8 | 0.24 ± 0.07                       |
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Fig. 1. The RGS spectrum of Mrk 335 (corrected for the source redshift). The fitted model, plotted as a red line, consists of a power law with $\Gamma \sim 2.7$ and the emission features reported in Table 2. The data have been binned according to the instrumental resolution only for plotting purposes (see text).

intercombination line emission and weaker resonant and forbidden lines (see Fig. 2 for a zoom on this spectral portion). The line ratios in He-like ions provide a powerful diagnostic of the physical properties of the emitting gas, mainly by indicating whether the X-ray lines are produced by collisional plasma, by photoionisation, or in a hybrid environment (Porquet & Dubau 2000; Porter & Ferland 2007). The line ratios from the present spectra were calculated with the OVIII Ly$\alpha$ and the OVII triplet lines. The numbers estimated are $G = \frac{(f + i)}{r} = 4.30 \pm 2.70$, $L = \frac{r}{i} = 0.38 \pm 0.25$, and $R = \frac{f}{i} = 0.65 \pm 0.33$, where $r$, $i$, $f$ indicate the intensity of the resonant, intercombination, and forbidden line components in the triplet. Given the high value of the $G$ ratio, albeit measured here with considerable uncertainties, the reported line ratios are consistent with an origin in photoionised gas and a possible contribution from collisional processes (Porquet & Dubau 2000).

Extensive simulations were run through the photoionisation code CLOUDY (Ferland et al. 1998) in order to constrain the physical properties of the emitting gas. The aim of these simulations was to extract the expected theoretical values for the line fluxes and to compare them to the observed fluxes. In addition to the line ratios cited above, we also consider the following ratios: $\frac{\text{CVILy}\alpha}{\text{OVIII Ly}\alpha} = 0.75 \pm 0.33$, $\frac{\text{CVILy}\beta}{\text{OVIII Ly}\alpha} = 0.65 \pm 0.33$, $\frac{\text{NVILy}\alpha}{\text{OVIIILy}\alpha} = 0.65 \pm 0.28$, and $\frac{\text{CVILy}\beta}{\text{CVILy}\alpha} = 0.86 \pm 0.53$. These line ratios were calculated assuming the fluxes from the first column in Table 2 i.e. assuming lines with a delta profile. The fluxes measured with non zero-width Gaussian profiles are nonetheless consistent with this estimate.

The theoretical line fluxes were calculated assuming the spectral energy distribution (SED) of a standard AGN as calculated by Korista et al. (1997). The treatment of the UV radiation field is particularly important when dealing with a high ratio between the intercombination and the forbidden lines. In fact, an intense UV source can provide enough photons to depopulate the forbidden level 2 $3S$ via photo-excitation and then pump the electrons into the intercombination level 2 $3P$, resulting in a more intense intercombination line (Mewe & Schrijver 1978; Kahn et al. 2001). We therefore compared the observed SED of Mrk 335 to the one assumed by CLOUDY. The UV spectrum as observed by the XMM-Newton Optical Monitor is in good agreement with the SED by Korista et al. (1997). The spectral slope of the UV-X-ray power-law commonly defined as $\alpha_{\text{ox}} = -0.3838 \log \frac{F_{\nu}(2 \text{ keV})}{F_{\nu}(2500 \text{ Å})}$ was estimated using the pn and OM fluxes at 2 keV and at 2340 Å, respectively giving $F_{2 \text{ keV}} = 0.53 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ keV$^{-1}$ and $F_{2340} = 2.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. The resulting UV-X-ray power
The simulations were carried out by varying the column density of the gas, an estimate of the gas size, and the ionisation parameter given above. The value \( \alpha_{\text{in}} = 10^{4.2} \) erg s\(^{-1}\) was adopted after Woo & Urry (2002). For each ionisation parameter \( U \), the values of the distance of the emitting gas cloud(s) from the nucleus and its size have been estimated. The minimum and maximum values correspond to the 99% contour for the range in electron and column density of the gas in Fig. 3. The solutions admitted by our data are summarised in Table 3 and they will be discussed in the following section.

### 4. Discussion

The RGS spectrum of Mrk 335 at low state provides a unique opportunity for getting insights into an X-ray reprocessing region that is not easily accessible in Seyfert 1 objects. The soft X-ray emission lines could be observed because of the decrease in the continuum flux. The nuclear power was attenuated for reasons as yet unknown, however the most straightforward explanation could be partial obscuration of the central source. At first glance, this object seems to be analogous to the other well-known case of an extremely variable Seyfert 1, NGC 4051, which showed a very rich emission line spectrum when it was observed in a low flux state by XMM-Newton (Pounds et al. 2004). According to these authors, the analysis of the emission lines in this source, especially of the OVII triplet, pointed to interpret the soft X-ray spectral features as arising from photoionised low-density gas distributed on a large scale, consistent with the AGN narrow line region. The variability history of Mrk 335 and the comparison with other variable AGN are not the prime focus of the present work. Nonetheless, the low-state, soft X-ray spectrum resembles the RGS spectra recently observed in obscured AGN by Guainazzi & Bianchi (2007). It is then reasonable to postulate that we are observing the same line-emitting gas in Mrk 335 as became observable due to the drop in the continuum flux. There

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**Table 3.** Summary of the physical properties of the gas clouds estimated from the 99% contour plot in Fig. 3.

| log \( U \) | \( n_e \) range | \( n_{\text{H}} \) range | dist range | size range |
|-----------|----------------|----------------|------------|-----------|
| 0.4       | \( 10^{5.8–11.1} \) | \( 10^{10.9–21.9} \) | \( 1.95 \times 10^{-17} \) | \( 10^{0.12} \) |
| 0.8       | \( 10^{5.5–11} \)   | \( 10^{20.3–22} \) | \( 1.95 \times 10^{-16} \) | \( 10^{0.13} \) |

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**Fig. 3.** Contour plots for electron and column density of the line emitting gas. The contours were obtained by comparing the ratios of the emission lines listed in Table 2 to the values predicted by CLOUDY simulations (see text for details). The curves define the 90 and 99% regions in the parameters space for all the eight line ratios. Only those values of the ionisation parameter yielding a valid solution have been plotted. The corresponding physical quantities are listed in Table 3.

**Fig. 4.** The cartoon shows qualitatively the location of the ionised gas in the nucleus of Mrk 335 on a scale of gravitational radii and the corresponding cm scale.
are some objections to this hypothesis. The main point is that, in many obscured sources, the soft X-ray photoionised matter was demonstrated to be coincident with the extended narrow line region, i.e. well out of the obscuring torus (Bianchi et al. 2006).

The scale of this gas is much larger than the distance of the emitter observed in Mrk 335 for all the possible solutions listed in Table 3. For this reason, the hypothesis of a common location of the soft X-ray photoionised gas for unobscured and obscured objects is discarded in the present case.

The simulations run with CLOUDY cannot uniquely constrain the ionisation parameter or the electron density of the gas, and yet they provide a range of physical conditions for the gas that are noticeably in agreement. The distance of the photoionised plasma from the nuclear source ranges approximately from 7 to 77 light days, meaning that the gas is always confined within ~0.06 pc. The column density never gets higher than 10^{22} cm^{-2} (see contours in Fig. 3) and the size of the emitting region(s) always appears quite small, the dimension of the largest cloud being ~10^{11} cm. From the black hole mass \( M = 1.42 \times 10^7 M_\odot \) (Peterson et al. 2004), the Schwarzschild radius \( R_{\text{S}} \) is estimated to be around 4 \times 10^{15} cm. The distance of the Broad Line Region (BLR) from the central source can be found by considering the width of the optical lines and assuming that the BLR gas is virialised. The H\beta FWHM was measured by Boroson & Green (1992), and it is equal to 1640 km s\(^{-1}\), in agreement with the reverberation mapping measurements provided by (Peterson et al. 2004). The BLR can then be located at \( \sim 7 \times 10^{10} \) cm, and that this gas in Mrk 335 is constituted of several clouds of emitting matter forming a clumpy medium was suggested by Arav et al. (1997) on the basis of observational constraints.

It is very likely that the X-ray photoionised gas is inner to the BLR clouds and it is also reasonable that the two materials form a distribution of clouds. One can imagine that the innermost clouds spread out towards the nucleus, releasing an ionisation level high enough to emit the observed soft X-ray lines. In this case, the spectral line should suffer line broadening due to the vicinity of the central black hole, although this effect should not be extreme because the Schwarzschild radius is 3 orders of magnitude smaller. The Gaussian line width measured in the OVIII Ly\(\alpha\) is estimated to be ~7 keV (Larsson et al. 2007; Grupe et al. 2008), implying that rapid line variability must be involved. The potential physical connection among the briefly outlined observational results and the soft X-ray lines in the present work should be a point of major interest in the next studies of this intriguing active galaxy.

Acknowledgements. This paper is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. The authors wish to thank the XMM-Newton Project Scientist Norbert Schartel for coordinating the observation and the release of the XMM-Newton data. We are grateful to many people within the XMM Science Operation Centre: Pedro Rodriguez-Pascual for his contribution on Mrk 335 Optical/UV SED; Andy Pollock for always being a wise advisor on the RGS data treatment, and Maria Diaz-Trigo for support with the use of the SPEX software. The authors thank R. Porter for help with CLOUDY simulations. We thank Dirk Grupe for a fruitful exchange of opinions on the XMM-Newton data, and we warmly thank Yair Krongold for many stimulating discussions on this paper during his visit at ESAC.

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