Statistical Methods for the Detection of Flows in Active Galactic Nuclei Using X-Ray Spectral Lines

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Abstract Using robust statistical methods, we are able to detect and identify absorption lines in the X-ray spectra of quasars and active galactic nuclei taking as reference the Seyfert 1 galaxy NGC 3783. The high resolution spectrum of this object shows evidence of partially ionized gas outflowing from the centre of the system at velocities of $\approx 625 \pm 35$ km s^{-1}. This velocity differs from a previously reported value by ≈ 6 %. The understanding of these flows is important to draw a general picture of the feedback observed between the analyzed objects and the host galaxy.

1 Introduction

Active Galactic Nuclei (AGNs) are galaxies with a huge amount of energy ($\sim 10^{(42-48)}$ erg s^{-1}) released from very compact regions at the centre of the system. Astronomers believe that this energy is radiated away by a flowing accretion disk formed around a rotating, supermassive black hole (SMBH) with $\sim 10^{(6-10)}\,M_{\odot}$, covering the whole electromagnetic spectrum from the radio to the X-ray and gamma ray wavebands. AGNs are classified in blazars, quasars, Seyfert 1 and 2, according to the unification model of AGN species (Osterbrock and Pogge 1985). This model establishes that different observational classes of AGN are really the same object seen from different orientation angles.

In this chapter, we present an analysis of the X-ray spectrum of the Seyfert 1 NGC 3783, taken with the spatial observatory *Chandra*. In the Seyfert galaxy NGC

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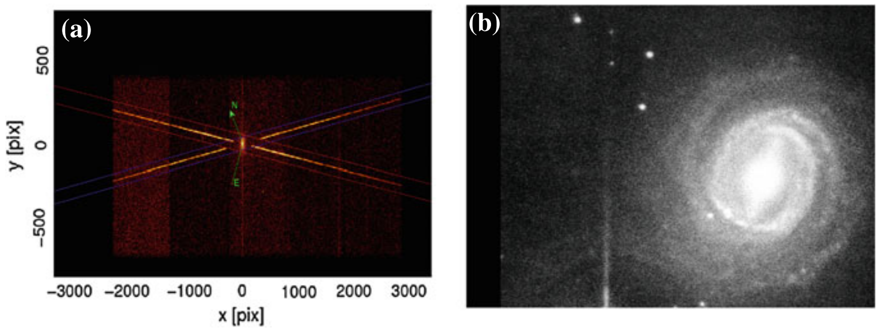

Fig. 1 **a** Image of NGC 3783 taken with the *Chandra* X-ray observatory **b** Image of the same AGN using the Hubble telescope

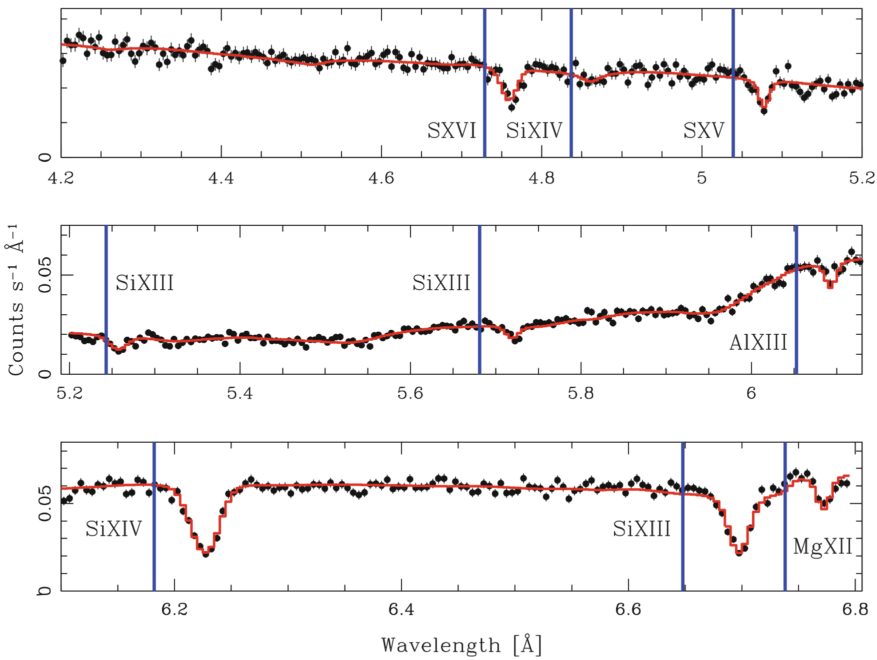

Fig. 2 X-ray spectrum of NGC 3783 in the range from 4.2 to 6.8 Å. The *vertical lines* mark the rest-frame wavelengths of the identified ions. The *solid line* shows the statistical continuum plus Gaussian model

3783, its 900 ks *Chandra* spectrum (Kaspi et al. 2002) allows for precise measurements of the radial velocities and line widths. It is seen that the shift of the spectral lines from Fe XXIII-Mg XII cover a range of velocities of ∼ 60–600 kms, while the lowly ionized lines Si XIII-O VII cover velocities of ∼ 500–1,000 kms (see Fig. 6 of Ramírez et al. (2005)). The average velocity of the warm/outflowing absorber

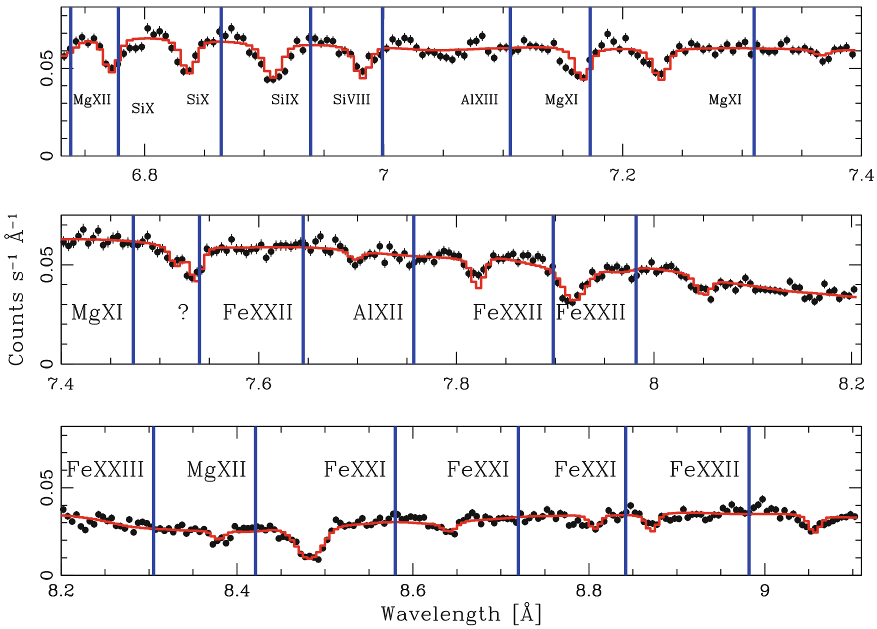

Fig. 3 X-ray spectrum of NGC 3783 in the range from 6.75 to 9.1 Å. The *vertical lines* mark the rest-frame wavelengths of the identified ions. The *solid line* shows the statistical continuum plus Gaussian model

of NGC 3783 is around ~500 km/s. The spectrum also reveals asymmetric line profiles (Kaspi et al. 2002), showing approximately 90 % of the lines with extended blue wings. Such asymmetries were quantified by Ramírez et al. (2005). In terms of ionization, most high ionization species are seen in the short-wavelength portion of the spectrum ~ 4–12 Å. Here, the resonant lines from Fe XXIII, Fe XXII, Fe XXI, S XVI, S XV, Si XIV, and Mg XII cover ionization parameters ξ in the range from ~630 to ~ 150 ergs cm s^{-1}. Figure 1 shows images of the galaxy as observed with the *Chandra* and Hubble telescopes.

2 X-Ray Spectral Lines of NGC 3783

Using specialized softwares (XSPEC 12.7.1 and CIAO 4.4), we have reduced and analyzed the data, consisting of six consecutive observations between 2000 and 2001, and then merged them to obtain a single high-resolution spectrum of 88,958 ks of exposure time. The work presented here is based on the MEG ± 1 (Medium Energy Grating) arms of the HETGS (High Energy Transmission Grating Spectrometer) on board *Chandra*. It results in 8,192 wavelength channels with 0.023 Å of instrumental resolution in the range from ~ 4.2 to 19.2 Å. It is interesting to see the several spectral

Table 1 Line measurements

Ion (Rest λ* -Å-)	Observed wavelength (Å)	Error Error (Å)	Doppler velocity (kms^{-1})	Error (kms^{-1})	Relative velocity (kms^{-1})	Error (kms^{-1})
SXVI 4.729	4.760	0.007	1,989	444	−928	461
SXV 5.039	5.080	0.004	2,458	238	−459	269
SiXIII 5.234	5.259	0.010	2,080	573	−837	586
SiXIII 5.681	5.721	0.015	2,048	792	−869	801
AlXIII 6.053	6.094	0.003	2,245	149	−672	194
SiXIV 6.182	6.228	0.003	2,265	145	−652	191
SiX 6.778	6.841	0.017	2,759	752	−158	762
SiX 6.864	6.909	0.019	1,939	830	−978	839
SiIX 6.939	6.984	0.011	1,924	475	−993	491
SiVIII 6.999	7.061	0.023	2,631	985	−286	993
MgXII 7.106	7.170	0.010	2,702	422	−215	440
MgXI 7.310	7.371	0.079	2,553	na	−364	na
MgXI 7.473	7.511	0.022	2,481	883	−436	891
AlXII 7.757	7.826	0.023	2,639	889	−278	898
FeXXII 7.982	8.055	0.023	2,742	864	−175	873
FeXXIII 8.305	8.381	0.032	2,724	na	−193	na
MgXII 8.421	8.484	0.006	2,250	214	−667	247
FeXXI 8.580	8.643	0.027	2,201	943	−716	952
FeXXI 8.720	8.810	0.022	3,068	756	151	767
FeXXII 8.982	9.058	0.027	2,510	901	−407	910
FeXX 9.080	9.151	0.040	2,336	1,321	−581	1,327
MgXI 9.169	9.245	0.017	2,479	556	−438	570
MgIX 9.378	9.451	0.628	2,323	na	−594	na
FeXXI 9.483	9.553	0.009	2,201	285	−716	311
NeX 9.708	9.781	0.006	2,257	185	−660	223
NeX 10.239	10.321	0.030	2,391	878	−526	887
FeXVIII 10.365	10.441	0.026	2,188	752	−729	762
FeXVII 11.026	11.084	0.016	2,322	435	−595	452
NeIX 11.547	11.628	0.019	2,102	493	−815	509
FeXXII 11.780	11.861	0.051	2,058	1,298	−859	1,304
FeXXI 11.952	12.031	0.065	1,981	1,630	−936	1,635
FeXXI 11.973	12.074	0.032	2,510	801	−407	811
FeXXI 12.576	12.651	0.038	2,121	906	−796	914
FeXX 12.588	12.681	0.059	2,212	1,405	−705	1,411
FeXX 12.846	12.934	0.015	2,055	350	−862	372
FeXIX 12.946	13.035	0.020	2,054	463	−863	480
FeXVII 13.825	13.923	0.033	2,108	716	−809	726
FeXVIII 14.158	14.271	0.053	2,391	1,122	−526	1,129
FeXVIII 14.208	14.312	0.045	2,177	950	−740	958
FeXVIII 14.373	14.381	0.045	1,830	939	−1,087	947
FeXVIII 14.534	14.651	0.036	2,413	743	−504	753
OVIII 14.634	14.751	0.062	2,396	1,270	−521	1,276

(continued)

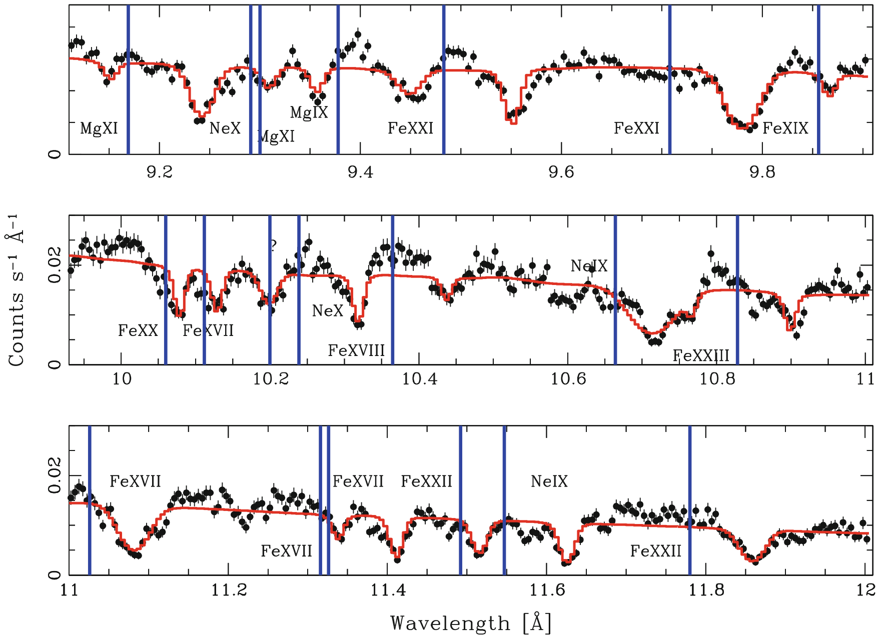

Fig. 4 X-ray spectrum of NGC 3783 in the range from 9.1 to 12.0 Å. The *vertical lines* mark the rest-frame wavelengths of the identified ions. The *solid line* shows the statistical continuum plus Gaussian model

Table 1 (continued)

Ion (Rest λ* -Å-)	Observed wavelength (Å)	Error Error (Å)	Doppler velocity (kms^{-1})	Error (kms^{-1})	Relative velocity (kms^{-1})	Error (kms^{-1})
OVIII 14.821	14.945	0.036	2,500	728	−417	739
FeXVII 15.014	15.121	0.037	2,138	739	−779	749
OVIII 15.176	15.295	0.030	2,336	593	−581	606
FeXVII 15.261	15.381	0.035	2,354	688	−563	699
OVIII 16.006	16.132	0.096	2,343	na	−574	na
OVII 17.396	17.528	0.090	2,258	1,551	−659	1,556
OVII 17.768	17.862	0.089	2,248	1,502	−669	1,507
OVIII 18.969	19.102	0.055	2,093	869	−824	878

features produced by H- and He-like ions in this band. Figures 2, 3 and 4 show the X-ray spectrum of NGC 3783 along with the theoretical global model we have used to detect and measure the line centroids.

The quality of the fit and the extraction of the errors were quantitatively measured using a χ^2-statistics (which gives a measure of the quadratic deviation between the data and the model). Furthermore, a single absorbed power-law was used for the global continuum and a Gaussian model for the characterization of the narrow-line features.

3 Results

We have measured a total number of 78 transitions of Si, S, Al, Mg, Fe, Ne and O. However, we were not able to identify about seven features associated to the measured lines in our database, thus giving the method an efficiency of ~ 91.76 %.

Once the line identification is completed, we compare the measured line centroids to the rest-frame wavelengths to obtain the radial velocities of the outflows using Doppler shift analysis. It is worth mentioning that for the velocity of the galaxy we have used a corrected value of $v_{\rm gal} = 2,917 \pm 2$ km s^{-1}.

The results are summarized in Table 1, which lists all ions identified, the measured wavelengths, and the Doppler and relative velocities observed in the flow. The errors in the wavelengths and velocities are also given.

4 Conclusions

We have detected and identified absorption lines in the X-ray spectrum of the Seyfert 1 NGC 3783 galaxy in the range from ~ 4.2 to 19.2 Å, with the purpose of measuring the average velocity of the partially ionized gas outflowing from its centre.

We find an average outflow velocity of -625 ± 35 km s^{-1}, which is of the same order of the value measured by Kaspi et al. (2002), with a difference of only 6 %. These flows have their likely origin in the accretion disk surrounding a supermassive black hole in the centre of the galaxy along with violent supernova explosions taking place in sites of star formation, and/or in strong magnetic forces that accelerate the flows to the observed velocities. Further work on other objects and more complex models would be required to improve our understanding of these systems.

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