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MULTIPLE VELOCITY COMPONENTS IN THE C IV ABSORPTION LINE OF NGC 5548¹

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ABSTRACT

We have observed the much-studied Seyfert 1 galaxy NGC 5548 with the Goddard High-Resolution Spectrograph (GHRS) on the *Hubble Space Telescope* (HST). Our 14 ks observation covers the C iv emission line at a resolution of greater than 20,000. Our purpose was to study the absorption line found at lower resolution by *IUE* and the *HST* Faint Object Spectrograph. We found that the C iv absorption line resolves into six separate doublets with equivalent widths of 0.07–0.38 Å. The absorption lines have blueshifts relative to the systemic velocity of the galaxy of 380–1250 km s^{−1}, except for one, which has a redshift of 250 km s^{−1}, suggesting both inflow and outflow. The inflowing component may be related to the accretion flow into the nuclear black hole. All the doublet lines are resolved by the GHRS. Three doublets are narrow, with FWHM ≲ 100 km s^{−1}, and three are broad, FWHM ∼ 160–290 km s^{−1}. We find evidence of partial covering by the narrow absorption lines. Either (but not both) of the two strongest broad doublets could be from the same material that produces the X-ray ionized absorber seen in soft X-rays. The remaining five systems must be at least 10 times less ionized (and so of lower total column density) to remain consistent with the X-ray spectra.

Subject headings: galaxies: individual (NGC 5548) — galaxies: kinematics and dynamics — galaxies: Seyfert — ultraviolet: galaxies

1. INTRODUCTION

The bright, variable Seyfert 1 galaxy NGC 5548 has been extensively studied at many wavelengths. It has been a target of reverberation mapping experiments in the optical and UV (Peterson et al. 1992; Clavel et al. 1991; Korista et al. 1995). These have led to the accurate determination of the physical size of the broad emission line region (BELR). The UV spectrum also shows absorption lines (Shull & Sachs 1993; Mathur, Elvis, & Wilkes 1995, hereafter MEW95), and monitoring observations place upper limits on the response time of the UV absorbers to changes in the UV continuum. The X-ray spectrum shows an ionized absorber (Nandra et al. 1991; Reynolds 1997; George et al. 1998). NGC 5548 is radio quiet, like most Seyfert galaxies, but it is not radio silent. Large radio lobes are observed in the plane of the sky, indicative of an edge-on nuclear geometry.

Recently, based on *ASCA* and *Hubble Space Telescope* (HST) Faint Object Spectrograph (FOS) data, MEW95 showed that the ionized X-ray and UV absorption in NGC 5548 are likely to originate in the same material. This unification allowed us to combine the X-ray and UV constraints to determine the physical conditions of the absorber. In the FOS data, the measured line widths for the C iv doublet are ∼ 350 km s^{−1} (FWHM), broader than the nominal spectral resolution for this observation (∼ 250 km s^{−1}) and thus possibly resolved. This would imply that the absorber is dispersed in velocity space.

High-resolution observations would allow accurate determination of the velocity spread parameter and resolve multiple components, if any. This in turn would allow better estimates of column density. We observed the C iv line in

NGC 5548 with the Goddard High-Resolution Spectrograph (GHRS) on *HST* with this aim in mind.

2. OBSERVATIONS AND ANALYSIS

We observed NGC 5548 with GHRS on *HST* on 1996 August 24. The exposure was centered around the C iv emission line. A total exposure time of 14,035 s was obtained using G160M in ACCUM mode covering the wavelength range 1554–1590 Å. The Large Science Aperture (1″.74 × 1″.74) was used, providing a spectral resolution of ∼ 20,000. We also observed with the lower resolution G140L grating for 2176 s to measure the complete line profile and part of the continuum on both sides of the line (1417–1713 Å).

Data reduction was performed using STSDAS in IRAF following procedures described in the *HST* Data Handbook. The wavelength shift in different groups of a single exposure, as well as between different exposures, was determined with the task POFFSETS by using the wavelength information in the associated calibration files.³

The groups were then aligned and combined using SPECALIGN. Wavelength and flux information was combined using MKMULTISPEC. The resulting total G160M spectrum, smoothed by a boxcar of 7 pixels, is shown in Figure 1.

The G160M spectrum clearly shows multiple components in the absorption-line profile. By using the wavelength difference in the C iv doublet components, we find that there may be as many as six different velocity components (Fig. 1). Accurate determination of absorption-line parameters is our primary goal, and so, to determine a reasonable estimate, we used three different methods to measure the absorption lines. First, we used SPLOT to measure the absorption-line equivalent widths (EWs) by

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³ The “standard” way of using the task POFFSETS misses out weak and narrow features present in this spectrum. We used it with “usecorr = no”.

FIG. 1.—GHRS G160M spectrum of C iv line in NGC 5548. It is smoothed to display the multiple absorption components clearly (marked 1–6).

simple linear interpolation across the line in the emission-line profile. This method is unable to measure the blended components 4 and 5 separately. We next fitted each absorption-line profile with a Gaussian function, again in SPLOT. These two sets of measurements served as the initial guesses of the EWs. To measure the correct EWs, we have to take into account the emission-line profile.

Fitting of the emission and absorption lines together was done using the STSDAS task SPECFIT (Kriss 1994). First we used the lower resolution G140L spectrum to fit the power-law continuum and the emission-line profile. The emission line was fitted with broad and narrow Gaussian profiles over the regions unaffected by absorption. These fit parameters were used in the subsequent fits to the high-resolution spectrum. The parameters of the power-law continuum, the slope, and normalization were fixed in all the fits to the high-resolution data. The true shape of the emission profile is the major unknown that affects the EWs of the absorption lines. To assess the range of probable EWs, we fitted the emission lines with three different line profiles, “high,” “medium,” and “low,” using slightly different parts of the emission line. Fits over the entire wavelength range were then performed by adding a Gaussian function for each absorption line. We performed over 10 different fits to obtain estimates of the absorption-line parameters. Initially, component 6 was not included in the fit, since this part of the spectrum might have been a part of the emission-line profile. However, adding this component increased the quality of the fit substantially, with a significant reduction in χ^2 . In Table 1 we report the EWs of the absorption lines

FIG. 2.—Four different line profiles fitted to and superposed on the C iv emission line.

for the four most acceptable fits (see Figs. 2 and 3). In fit 1 we fixed the parameters of the emission line to the low profile. In fit 2 we fixed these parameters to the medium profile. In fit 3 we allowed these parameters to vary. The shape of the emission-line profile in this case is close to the high profile (see Fig. 2). The width of both doublet lines in a given component was required to be the same, although different from component to component, and $\Delta\lambda$ was kept constant (at 2.64 Å). Except for these constraints, the absorption-line parameters (EW, centroid, and FWHM) were allowed to be free. Inspection of these results (Table 1) shows that the doublet ratios for most of the absorption components are not equal to the value of 2 required by atomic physics for optically thin gas (except for components 3 and 6 in fit 2). Given the small EW of the lines, saturation is unlikely to be the cause. For lines with low EWs, partial covering of the continuum source might be the cause of doublet ratios close to 1. We discuss this in details below. We also performed one more fit (fit 4) by fixing the doublet EW ratio to 2 and allowing the emission-line parameters to be free to vary. The shape of the emission-line profile in this case is even higher than the high profile (Fig. 2), which seems unlikely. The fit in this case is also significantly worse than for fits 1–3.

Fit 2 gives the statistically best fit, and in Table 2 we list the EW, FWHM, centroid wavelength, and C iv column density inferred for each component for this case. We note,

TABLE 1
OBSERVED ABSORPTION-LINE EWs (Å)

Fit ^a	COMPONENTS											
	1(1)	1(2)	2(1)	2(2)	3(1)	3(2)	4(1)	4(2)	5(1)	5(2)	6(1)	6(2)
1.....	0.1	0.003	0.08	0.06	0.3	0.1	0.38	0.28	0.29	0.22	0.01	0.04
2.....	0.11	0.005	0.08	0.07	0.33	0.17	0.33	0.24	0.38	0.30	0.13	0.06
3.....	0.09	0.01	0.09	0.08	0.44	0.25	0.33	0.25	0.41	0.29	0.45	0.37
4.....	0.07	0.035	0.09	0.04	0.2	0.1	0.30	0.15	0.43	0.21	0.82	0.41

^a (1) and (2) represent shorter and longer wavelength components of a doublet.

FIG. 3.—Superposition of the four fits to the emission + absorption lines on the data.

however, that these values are not unique, since fit 3 is statistically indistinguishable from fit 2. The fit 2 derived parameters of the emission lines, flux, centroid, and FWHM, are also listed in Table 2. The large range in the EWs resulting from different fits (typically a factor 2–3 but even a factor of 10 in some cases) is clearly seen in Table 1 and indicates the uncertainty in these measurements. However, as discussed elsewhere, emission-line profiles in fits 1 and 4 are unlikely to be true. Considering only fits 2 and 3, the scatter in EWs ranges from a factor of 1 for component 4(1) to a factor of 5 in component 6(2).

3. THE UV ABSORBERS

The C IV absorber has six clear, distinct velocity components (marked as components 1–6 in Fig. 1). Components 1, 3, and 6 are broad (with $\text{FWHM} > 150 \text{ km s}^{-1}$; Table 2), while components 2, 4, and 5 are narrow. Note that the EW of the weak line of component 1 [1(2)] is at $\lesssim 1 \sigma$ level for all fits, except for fit 4, where it was constrained to be higher. It is therefore possible that component 1 is spurious. Similarly, EW of component 6(2) is barely at the 3σ level for fit 1. So we believe that the low profile may not be the correct description of the emission line. The doublet ratios of the broad components in fit 2, the best fit, are close to 2, while for the narrow components the ratio is systematically smaller. We investigated whether partial covering might be playing a role for the narrow components. Following Hamann et al. (1997) we measured the residual intensity at the troughs of the absorption lines and determined the covering fraction C_f using their equation (5). We found C_f to be 0.39, 0.99, and 0.73 for components 2, 4, and 5, respectively. Based on flux errors, we estimate errors on C_f to be 7.5%, 13.5%, and 15% for components 2, 4, and 5, respectively. Thus it is likely that the closely spaced components 4 and 5 have the same covering fraction of ~ 0.85 , with component 2 having about half that value. “Partial covering” may be due either to a simple geometrical factor or to “filling in” of the absorption lines by scattered continuum as in broad absorption line QSOs (BALQSOs; Cohen et al. 1995).

The C IV column density in each component was calculated by integrating the optical depths over the absorption-line profile (Savage & Sembach 1991) for (1) complete coverage ($C_f = 1$) and (2) partial coverage ($C_f < 1$), assuming constant C_f across the line for narrow lines. We used equation (6) in Hamann et al. (1997) to calculate optical depths in case of partial covering. The resulting values of $N(\text{C IV})$ for fit 2 are given in Table 2. We also calculated $N(\text{C IV})$ using the measured EWs and assuming the line to be on the linear part of the curve of growth, a

TABLE 2
ABSORPTION- AND EMISSION-LINE PARAMETERS FOR FIT 2 (MEDIUM EMISSION-LINE PROFILE)

PARAMETER	ABSORPTION COMPONENTS ^a											
	1(1)	1(2)	2(1)	2(2)	3(1)	3(2)	4(1)	4(2)	5(1)	5(2)	6(1)	6(2)
EW	0.11	0.005	0.08	0.07	0.33	0.17	0.33	0.24	0.38	0.30	0.13	0.06
FWHM ^b	291	291	39	39	165	165	67	67	103	103	168	168
Centroid	68.70	71.32	70.82	73.43	71.54	74.16	72.39	75.01	72.75	75.36	76.09	78.70
$\lambda 1500 + ^c$												
$cz^{b,c}$	3900		4380		4500		4680		4770		5400	
$\log N^d$		12.4		13.5		13.9		14.1		14.2		13.6
$\log N(C_f = 1)^e$		12.4		13.6		13.9		14.2		14.3		13.4
$\log N(C_f < 1)^f$				14.2				14.2		14.4		
Emission Line	Flux ^g		Centroid ^g		$cz^{b,c}$		FWHM ^b					
Broad	5.9E–12		1574.73		4950		6978.85					
Narrow	8.6E–13		1575.60		5130		1074.18					

^a (1) and (2) represent shorter and longer wavelength components of a doublet.

^b In units of km s^{-1} .

^c These are as measured from the SPECFIT fit. We estimate a systematic wavelength offset of $\sim 0.095 \text{ \AA}$ or a redshift by $\Delta cz \sim 18 \text{ km s}^{-1}$ caused by the manipulation of the raw data.

^d From EWs, assuming the linear part of curve of growth.

^e From integrating optical depths over the line profile, assuming a covering fraction of 1.

^f Using a constant covering fraction less than 1 across the line for narrow lines. See text for values of C_f .

^g In units of $\text{ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$.

very good assumption given the low EWs and observed FWHM of the lines. The values of $N(\text{C IV})$ from this method are similar to those obtained from the optical depth method within 0.1 dex (see Table 2). The scatter in $N(\text{C IV})$ from all the fits 1–4 is about 0.2 dex for component 5 and 0.3 dex for components 2, 3, and 4. The errors are larger, about an order of magnitude, for component 6, which is closest to the emission-line peak, where the emission-line profile is most uncertain. Clearly, the uncertainty in column density is governed by the uncertainty in the underlying emission-line profile.

The resolution of GHRS is $\approx 20,000$, corresponding to $\sim 15 \text{ km s}^{-1}$ at $1575 \text{ \AA}$. So all the absorption lines are resolved with FWHM ranging from $\sim 40 \text{ km s}^{-1}$ for component 2 to $\sim 300 \text{ km s}^{-1}$ for component 1. The thermal width of carbon in a 10^4 K gas is about 4 km s^{-1} , and that of a 10^5 K gas is about 12 km s^{-1} . Since photoionization models based on X-ray observations imply temperature $\lesssim 10^5 \text{ K}$, this is about the highest temperature allowed for C IV absorption systems. The total column densities would otherwise be even higher. The implication is that there are nonthermal velocities, possibly due to bulk or turbulent motions, involved with the absorbing flows.

Except for components 1 and 6, the absorption lines are deeper than the power-law continuum emission. The absorbing gas must cover the BELR, at least partially, and so must lie outside the BELR. The only other possibility is that the system is absorbing flux from the far side of the BELR and so may be copatial with it.

4. DISCUSSION AND CONCLUSIONS

The systemic redshift of NGC 5548 is uncertain to about hundred km s^{-1} . As reported by de Vaucouleurs et al. (1991), the 21 cm H I velocity is 5149 km s^{-1} ($z = 0.017175$), while the optical emission-line measurements give 5026 km s^{-1} . Shull & Sachs (1993) used 5133 km s^{-1} , while $cz = 5220 \text{ km s}^{-1}$ was used in the *IUE* campaign (Clavel et al. 1991). The observed GHRS redshift of the broad emission line is $cz = 4950 \text{ km s}^{-1}$, and that of the narrow emission line is 5130 km s^{-1} (Table 2), consistent with the H I measurement. The broad line is blueshifted by 180 km s^{-1} with respect to the narrow line.

The narrow absorption lines have $\text{FWHM} \lesssim 100 \text{ km s}^{-1}$ and could arise in the interstellar medium or halo of the host galaxy. The broad components, on the other hand, are likely to be located closer in the nucleus. The broad components also fully cover the C IV emission region. A simple geometrical arrangement would be to have the broad absorbing region outside, but attached to, the BELR and of similar size. The redshifts of absorbing components range from $cz = 3900 \text{ km s}^{-1}$ for component 1 to $cz = 5400 \text{ km s}^{-1}$ for component 6 (fit 2). While broad components 1 and 3 indicate material outflowing from the nucleus with velocities 1050 and 450 km s^{-1} , respectively, component 6 must be associated with an inflow with a velocity of 450 km s^{-1} with respect to the BELR, suggesting an outflow as well as an inflow in the nuclear region of NGC 5548. However, the broad C IV emission-line peak and the absorption systems 1–5 are outflowing with respect to the host galaxy H I velocity. Component 6 is inflowing with respect to the H I velocity as well. There is no systematic trend of line properties, FWHM, or EW, with redshift offset, possibly due to random motions. Clearly, the kinematics of the nuclear region in NGC 5548 is complex. Done & Krolik (1996) have

studied the kinematics of the BELR in NGC 5548 and based on velocity-resolved reverberation mapping found evidence for significant radial infall in addition to random motions. Our observations of absorption-line components support their claim but give strong evidence of outflow as well. The infalling component 6 might be related to the accretion flow onto the central black hole.

As discussed earlier, NGC 5548 contains an ionized X-ray absorber. Is the X-ray absorber related to any of the UV absorbers seen in the GHRS spectrum? Based on the model of the X-ray absorber (see MEW95 for details), the predicted C IV column density is $2\text{--}7 \times 10^{13} \text{ cm}^{-2}$. (Note that this is an order of magnitude smaller than that derived in MEW95 because of subsequent significant changes in the photoionization code CLOUDY; Ferland 1996. For the present calculations we have used the latest version [90.04] of CLOUDY.) Given the C IV column density in the absorption-line components (Table 2), the X-ray warm absorber is likely to be associated with one of the broad components, either 3 or 6. [However, this conclusion could change if further updates to CLOUDY produced a factor of 3 change in predicted $N(\text{C IV})$.] If component 6 is indeed related to the accretion flow and thus is cold, then the X-ray ionized absorber may likely be related to component 3.

The definite way to resolve this is with high-resolution X-ray spectroscopy. As yet there is no X-ray spectroscopy anywhere close to GHRS resolution, so direct tests are not possible. The broad components 3 and 6 are separated by $\Delta z = 0.003$, corresponding to $\sim 2 \text{ eV}$ at the O VII edge of the warm absorber. High-resolution observations with *AXAF* would be able to determine the edge energy accurately enough to tell them apart. The absence of greater X-ray absorption implies that the remaining C IV components must have a much lower ionization state and smaller total column density by at least an order of magnitude.

Kinematically complex UV absorption, similar to that reported here, is also present in other Seyfert galaxies, e.g., Mrk 509 (Crenshaw, Bogges, & Wu 1995), NGC 4151 (Weymann et al. 1997), and NGC 3516 (Kriss et al. 1996; Crenshaw et al. 1999). All of these objects also show the presence of an X-ray warm absorber, qualitatively similar to that in NGC 5548 (Reynolds 1997; Warwick et al. 1996; Mathur, Wilkes, & Aldcroft 1997 for Mrk 509, NGC 4151, and NGC 3516, respectively). In Mrk 509 and NGC 4151, parameters of the warm absorber are not well constrained because of the complexity in X-ray spectra; as a result, comparison with UV absorption is difficult. The UV absorption system in NGC 3516 also shows narrow as well as broad components. However, the broad components have disappeared since about 1992. Mathur et al. (1997) have shown that an evolving X-ray/UV absorber is consistent with the presence of an X-ray warm absorber, the presence of broad UV absorption in the *IUE* data, and their disappearance in the recent UV observations. Our GHRS observations of NGC 5548 thus mark the first case in which complex UV absorption is present and for which a meaningful comparison with X-ray absorption can be made. It should also be noted that the UV absorption in a high-resolution GHRS observation of NGC 3783 is also found to be consistent with X-ray absorption (Shields & Hamann 1997), although the UV absorption in that case is not kinematically complex.

Even though our unified X-ray/UV absorption scenario (MEW95 and references therein) has stood the test of high-

resolution observations, it may not be adequate to explain complex systems in its present single-zone, photoionization equilibrium form. Multizone, multiparameter models will be required when the absorption systems show multiple components (e.g., objects in Hamann 1997). In some highly variable objects (e.g., NGC 4051), nonequilibrium models might be necessary (Nicastro et al. 1999). The X-ray/UV models should evolve and become more refined as better quality data become available (see Mathur 1997). At present, all the available data (Mathur, Wilkes, & Elvis 1998) clearly suggest that the UV and X-ray absorbers are

physically related and perhaps identical; at a minimum the X-ray absorption makes a substantial contribution to the absorption seen in the UV.

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