BALMER AND He I ABSORPTION IN THE NUCLEAR SPECTRUM OF NGC 4151

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ABSTRACT

Spectra taken with the Space Telescope Imaging Spectrograph allow accurate location and extraction of the nuclear spectrum of NGC 4151, with minimal contamination by extended line emission and circumnuclear starlight. Spectra since 1997 show that the P Cygni Balmer and He I absorption seen previously in low nuclear states is present in higher states, with outflow velocity that changes with the nuclear flux. The phenomenon is discussed in terms of some of the absorbers seen in the UV resonance lines, and in terms of outflows from the central source and surrounding torus.

Key words: galaxies: individual (NGC 4151) — galaxies: Seyfert

1. INTRODUCTION

NGC 4151 is the brightest Seyfert 1–type galaxy and has been studied in considerable detail at all wavelengths. In reference to the nuclear region, the Hubble Space Telescope (HST) has been instrumental in resolving the innermost few arcseconds and revealing the spatial and velocity structure of the narrow emission line gas (see, e.g., Hutchings et al. 1998; Kaiser et al. 2000; Nelson et al. 2000; Crenshaw et al. 2000). The detailed picture that emerged, for NGC 4151 and other Seyfert galaxies, is of a hollow biconical outflow of narrow-line clouds. In the case of NGC 4151, the high-velocity radio jets lie along the cone axis, and our line of sight lies close to the edge of the approaching cone. This scenario was put forward earlier by, for example, Pedlar et al. (1993) and Boksenberg et al. (1995).

NGC 4151 is also known to show flux variations over a factor of 10 or more, and it has been the subject of echo-mapping observational campaigns. These have shown the inner broad emission line region to have an extent of several light-days (see overview by Peterson et al. 1998). The brightness and spatial extent of the narrow emission lines have made it difficult to isolate the nuclear spectrum and emission lines. It was noted originally by Anderson & Kraft (1969) that there are shortward-shifted absorptions in Hγ and the metastable He I 3888 Å line. Anderson (1974) followed up with further data and a discussion that suggested a connection between the continuum flux and the absorption strength. This has been poorly documented since, but Sergeev, Pronik, & Sergeeva (2001) give a summary of observations over 11 years that show the absorptions are present in a nuclear low state in 1999. No systematic study has been made of the absorptions, perhaps because ground-based observing conditions cause a large range of contamination by the circumnuclear flux, both line and continuum.

The long-slit (or slitless) spectroscopic capability of the Space Telescope Imaging Spectrograph (STIS), along with the spatial resolution of HST, has made it possible to obtain and study the nuclear spectrum consistently and cleanly. There is extended narrow-line emission with many velocity components, even within the central arcsecond, which can affect the overall line profiles, if included. In this paper, we discuss the series of visible-range nuclear spectra from STIS, which fortuitously cover a wide range of nuclear flux variations. We are particularly interested in the outflow absorption that is seen in the strong Balmer and the metastable He I lines.

Outflow is also seen in higher velocity emission-line clouds near the nucleus (Hutchings et al. 1999), multiple shifted absorption lines in C iv and other UV resonance...
lines (Weymann et al. 1997; Crenshaw et al. 2000; Kriss et al. 2002), and warm absorbers seen in X-ray data (see, e.g., Schurch & Warwick 2002). A full picture of the different outflows has yet to emerge, and this paper adds further information to the inventory.

2. OBSERVATIONS AND DATA

Table 1 shows the observations used in this paper, along with some principal measures. With one exception (2000 June), the observations were executed as programs by the authors, so the data are known to be suitable for this investigation. In addition to the spectra listed in Table 1, we inspected and measured associated STIS spectra covering the far-UV to 1 µm, to obtain a complete picture of the nuclear spectrum at the same times. The spectral resolution at Hβ is ~800 for the G430L and ~8000 for the G430M spectra.

The nuclear flux varied considerably over the time span covered, including some unusually low states. The nuclear spectrum was extracted from the long-slit (or slitless) data by using the detector rows that covered the continuum, clearly detected. These were collapsed to a single spectrum and used for further measurements. The data were retrieved from the Canadian Astronomy Data Centre with on-the-fly calibration and also extracted using CALSTIS from the STIS team database. Two observations were made nominally offset by 0′09 from the nucleus (1998 June and 1999 June). The nuclear continuum is clearly present in the spectra, but the slit should have lost some of the flux. From the nuclear cross sections in the other spectra, we estimate that the continuum fluxes for these spectra may be underestimated by a factor of 2.5, and this factor is included in the Table 1 values. We note that the overall correlation with nuclear flux is not altered by this correction, or by an uncertainty of a further factor of 2 in either direction.

Figure 1 shows the average of the five G430L spectra as extracted this way, after each had been normalized to the continuum, and Figure 2 shows the comparison of the two G430M spectra (not normalized, as the coverage was not sufficient to establish the continuum level).

The asymmetry of the Hβ profiles (and other Balmer lines) is apparent in Figures 1 and 2. The profiles consist of a broad emission, a narrow emission, and a shortward absorption trough. The Hγ line is blended with [O III] λ4363 emission, and Hδ is blended with [S II] emission. We also note the absorption feature near 3900 Å, which is unique in the nuclear spectrum.

In Figure 3, the Balmer lines Hβ, Hγ, and Hδ are superposed in velocity space, after scaling to the same broad emission line profile peaks. The figure also sketches in a symmetric broad emission profile for the profiles from each observation. This was derived by folding the profile about zero velocities near zero and matching the unblended parts of them on each side. The agreement among the three Balmer lines is notable and lends confidence in the result. Note that in all cases there is an apparent shortward absorption, and that it is much more obvious in the later spectra, when the continuum level was very low. In the 1999 June spectrum, the Balmer absorption extends to higher velocities, beyond the deep minimum that corresponds to the main feature seen in other low-state spectra. We measured this absorption as two separate features in this spectrum.

We also note that the centers of the symmetric broad Balmer emission profiles are consistently longward of the

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**Table 1**

| DATE        | ID  | G430, Slit | 4800 Å Flux | H/β Absorption Measurements | He i λ3888 | λ4686 |
|-------------|-----|-----------|-------------|-----------------------------|------------|------|
| 1997 Jul 15 | 645 | M, 50     | 6 × 10^-14  | 0.6, 1.3 × 10^-13, -1850, -1200, ... | ... | 1.1  |
| 1998 Jan 8  | 822 | L, 0.1    | 7 × 10^-14  | 0.4, 1.4 × 10^-13, -2000, -1200, -530, 0.6 | 1.1      |
| 1998 Feb 10 | 855 | L, 0.1    | 6 × 10^-14  | 0.6, 1.4 × 10^-13, -2200, -1100, -580, 0.8 | 1.3      |
| 1998 Jun 14 | 966 | L, 0.1    | 2.5 × 10^-14 | 0.8, 1.1 × 10^-14, -1600, -750, -365, 1.5 | 1.4      |
| 1999 Jun 4  | 1334| L, 0.1    | 7 × 10^-15  | 6.2, 4.3 × 10^-14, -920, -460, -370, 1.8 | 4.3      |
| 2000 May 24 | 1689| L, 0.1    | 1 × 10^-14  | 1.8, 4.0 × 10^-14, -1135, -605, -495, 1.4 | 5.0      |
| 2000 Jul 2  | 1728| M, 0.2    | 6 × 10^-15  | 3.2, 7.0 × 10^-14, -990, -500, ... | ... | ... |

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*a* Flux in ergs cm^-2 s^-1.

*b* Absorbed flux in ergs cm^-2 s^-1.

*c* Radial velocity (km s^-1) with respect to redshift of 1000 km s^-1.

*d* Flux corrected by 2.5 for slit offset.
1000 km s$^{-1}$ generally quoted for NGC 4151, by an average of 350 km s$^{-1}$. (This standard value is presumably derived from the mean of many blended narrow emission peaks of different velocity over the nuclear region and, hence, somewhat arbitrary.) It may thus be that the velocities recorded in Table 1 should be more negative by this amount, to represent velocities with respect to the central broad-line region (BLR). However, we note that in earlier bright epochs, the broad emission line profiles are stronger on the shortward side of the nominal redshift (see Sergeev et al. 2001), so that there may be changes in the broad profiles (which may be caused by changing obscuration of the redshifted outflowing matter on the other side of the nucleus), and our symmetric assumptions in Figure 3 may not apply to other epochs.

Table 1 shows the measures of the Balmer absorption, as well as the equivalent width (EW) of the He I $\lambda 4686$ peak. This latter has a broad emission component too, but the peak (as all other narrow emissions) largely varies in EW as a result of the continuum changes, and the values serve as a consistency check on the continuum flux numbers. We define the $V_{\text{min}}$ value as the turning point of a parabola fitted to the absorption profile, and $V_{\text{edge}}$ as the shortward limit of absorption, as illustrated in Figure 3.

Finally, we measured the velocity of the minimum of the $\sim 3900$ Å absorption, assuming the identification is He I $\lambda 3888$. The decrement of the Balmer absorption and emission suggest this identification, plus the facts that this metastable-state line is known to arise in high-density outflows and that the velocities do not agree with the other Balmer absorptions. Anderson & Kraft (1969) made the same argument. The absorption lies between two emission lines (see Fig. 1), so a concern is that changes may be distorted by blending. However, we find no changes in the absorption or emission FWHM in the sense that the velocity changes would require if the lines were blended, so we conclude that the absorption feature is resolved with the G430L spectra.

We measured the absorption EW with respect to the continuum beyond the neighboring emissions, which may underestimate the true value. However, the measurements are well defined and consistent and also show a similar variation to the H$\beta$ absorption.

If we use the [Ne II] or [O III] emission as a wavelength fiducial instead of the data calibration, we find the absorption velocities may change by up to 50 km s$^{-1}$. This will not reduce the significance of the H$\beta$ changes, but these values are comparable to the He I range in Table 1. Variable inclusion of different narrow emission components in the different spectra are a more likely explanation of their velocity scatter, however. In Figure 4, we show the line velocities and absorption strengths as a function of the continuum flux at 4800 Å. We discuss the correlations further below.

In addition to the spectra listed in Table 1, we extracted spectra from the G750L, G230M, G140L, and G140M gratings taken at the same times. These spectra show that the derived fluxes exhibit no discontinuities from 1200 Å to 1 μm. We also inspected and measured major line features in these wavelengths, including H$\alpha$, Mg II $\lambda 2800$, and C IV, Si IV, N v, and Ly$\alpha$ in the far-UV. The H$\alpha$ line is strong and blended with [N II], so it is not useful for studying the absorption (although it clearly is present, in the form of asymmetry of the shortward side of the peak). The far-UV lines have been discussed in detail by several other authors, and below we discuss possible correlations with the varying Balmer and He I absorption in the G430 spectra. The C IV profile shows many absorption components shortward of line center, and these appear as a single smooth profile in the low-dispersion spectra. However, our G430M spectra show clearly that the H$\beta$ absorption is a single broad feature.
and not resolvable into sharp components as seen in the UV resonance lines. This too relates to our discussion below.

We measured the absorption FWHM values where possible—that is, the He i absorption, and the deep absorption profiles in the 1999 and 2000 spectra. The He i line is consistent with a value of 460 km s\(^{-1}\) for all cases, while the Balmer absorption is 340 km s\(^{-1}\) in the G430L spectra and 420 km s\(^{-1}\) in the 2000 July G430M spectrum. Smoothing the G430M spectrum to the resolution of the G430L does not alter the FWHM value, so the profiles are resolved in all spectra.

3. DISCUSSION

The presence of Balmer and He i \(\lambda 3888\) absorption indicates the presence of relatively high density and low ionization outflowing material. Furthermore, the outflow is apparently connected to the variations in the continuum flux. While the H\(\beta\) absorption has been noted before in low continuum states, it has not been isolated well from extended line emission or correlated with the nuclear variations.

We find that there is an asymmetry in the Balmer profiles at all nuclear flux states that may be measured as an outflow (P Cygni) absorption, and that in fact the absorbed flux is largest when the nucleus is in a high state. We also find that the velocity of the outflow is highest in the high nuclear state. The He i absorption shows a similar correlation but at lower outflow velocities. While the Balmer line measures in the high nuclear states depend on assuming the broad profile is symmetric (Fig. 3), and as the broad profiles do on other occasions have considerable blueward asymmetry, we may be wary of these measured values. However, the correlation with nuclear flux, the close agreement among three Balmer lines, and the changes in the (broad-component–free) He i line suggest the effects are real.

There are outflow absorptions seen in the far-UV resonance lines, which have been discussed in detail (e.g., Weymann et al. 1997; Crenshaw et al. 2000; Kraemer et al. 2001). Most of these absorbers are narrow and do not change by much, if at all, and may arise in clouds similar to those responsible for the narrow emission lines, from an extended region outside the BLR. However, there are some broader absorbers in the UV lines—in particular, component D+E of Kraemer et al. (2001), which has velocity \(-490\) km s\(^{-1}\) and FWHM \(435\) km s\(^{-1}\). This component has a high density of absorbing material and may give rise to Balmer absorption too. The H\(\beta\) EW of 3.2 (2000 July) implies a column of \(1.5 \times 10^{14}\) cm\(^{-2}\), while the EW for He i of 1.4 (2000 May) implies \(1.8 \times 10^{14}\) cm\(^{-2}\) if they are associated with a response of UV component D+E to changes in the ionizing continuum. It seems likely that this UV absorber is the same as that causing the low-velocity strong Balmer absorption in the nuclear low state. However, the connection with the higher velocity Balmer absorption and the lower velocity He i absorption is not clear.

In the higher nuclear states, the Balmer and He i velocities increase, as seen in Figure 4. These Balmer profiles do not appear to be composed of two or more components, and the complex absorption spectra in the UV resonance lines do not appear to include such changes. On the other hand, the He i absorber shows much less change in velocity. Thus, association of the Balmer and He i absorbers with components of the highly ionized species C iv, Si iv, and N v is unclear. The \(FUSE\) spectrum of NGC 4151 in a low flux state shows smooth, broad absorption profiles in O vi. These will be discussed in detail by Kriss et al. (2002), but for this discussion, we assume they arise in an accelerating flow from the central disk, as discussed for NGC 3516 in Hutchings et al. (2001).

NGC 4151 is often noted as being a marginal Seyfert 1 type, and the outflow models for the narrow-line region (NLR) gas suggest that the line of sight lies close to the edge of the opening cone of the ionizing radiation (see, e.g., Crenshaw et al. 2000). This means that whatever is defining the cone lies close to the line of sight. This is generically referred to as the obscuring torus. It is very reasonable to propose that the nuclear activity is causing some erosion of the edge of the torus, and this may be where the outflows we see in H and He i arise. The radiation effects that drive the flow will vary with the nuclear flux and lead to the velocity-flux correlation we see in Figure 4, with some time delay. A sudden drop in nuclear flux may leave a weakening broad absorption profile that lasts until the high-velocity flow has dispersed; this is possibly what we see in the 1999 June profiles, since UV spectra from a few months earlier show the nuclear flux to be much higher. By contrast, the low state of 2000 June was preceded by low flux in 2000 April.

The lower outflow velocity seen in the He i absorption must be significant. It suggests an acceleration in a cooling medium, as in stellar winds. It is interesting that Anderson & Kraft (1969) saw the same velocity difference, reinforcing our conclusion that the He i absorption is not significantly blended with the neighboring [Ne iii] emission line.
Anderson (1974) reported structure within the He I absorption, which is comparable to the noise in his spectra (and may also involve variable off-nuclear contamination). This is not resolvable in our G430L spectra. However, we note that the 10 times higher resolution G430M spectra of Hβ show very smooth absorption profiles (see Fig. 2).

The flow velocities are similar to those seen in the NLR and the associated sharp absorptions in the UV resonance lines. They are smaller than the higher velocity flows seen in the inner NLR (Hutchings et al. 1999), even without the projection effects that must apply to emission-line clouds. They are also somewhat smaller than the flow velocities seen in winds from massive stars (e.g., Fullerton et al. 2000). The flux from the nucleus of NGC 4151 is in the range of $10^5$ to $10^6$ times that of an OB star, so the radiation pressure would be similar at a distance of $3.5 \times 10^{15}$ cm, or 0.001 pc, if we want the same process to apply. The time lag over this distance is on the order of 1 day, which places it within the BLR by the echo-mapping results. However, we see no unambiguous evidence that the higher velocity flow shows up in the UV resonance lines, which are the principal drivers of stellar winds. Thus, it is possible that the flow reported here may arise in a more distant location and that some other force than central radiation may drive it.

It thus seems possible that the outflow arises in a high-density region (such as the torus edge) that is heated by both the nuclear radiation and outflowing material. The mild heating and acceleration we see may arise by entrainment in the biconical outflow. In very high nuclear states (not sampled in the data in this paper), the broad emission line profile changes asymmetrically, and perhaps the low-ionization outflow velocity is higher, so that it may be more difficult to identify it in the line profiles. It will be instructive to continue to monitor the nuclear visible spectrum through higher nuclear flux states. The special NGC 4151 line-of-sight geometry may be a valuable clue to the origins of the nuclear outflows.

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