FUSE OBSERVATIONS OF GALACTIC AND INTRINSIC ABSORPTION IN THE SPECTRUM OF THE SEYFERT 1 GALAXY 2MASX J21362313−6224008

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ABSTRACT

We present the far-ultraviolet spectrum of the Seyfert 1 galaxy 2MASX J21362313−6224008 obtained with the Far Ultraviolet Spectroscopic Explorer (FUSE). The spectrum features absorption from Galactic O vi at two velocities and redshifted H i Lyβ and γ, C ii, C iii, and O vi. The redshifted absorption features represent a single kinematic component blueshifted by \( \sim 310 \text{ km s}^{-1} \) relative to the active galactic nucleus. We use photoionization models to derive constraints on the physical parameters of the absorbing gas. An alternative interpretation for the absorption lines is also proposed, wherein the absorbing gas is associated with an intervening galaxy cluster.

Subject headings: galaxies: clusters: general — galaxies: individual (2MASX J21362313−6224008) — galaxies: ISM — ultraviolet: galaxies

1. INTRODUCTION

A large fraction of Seyfert 1 galaxies exhibit intrinsic UV absorption associated with their active galactic nuclei (AGNs). The absorption lines are commonly blueshifted with respect to the source, indicating that the absorbing material undergoes a net radial outflow (e.g., Crenshaw et al. 1999). The absorbing material is interpreted as photoionized gas with ionization parameter \( U \approx 0.01−0.1 \) and total hydrogen column density \( N_H \approx 10^{18}−10^{21} \text{ cm}^{-2} \) (Kriss et al. 2000, 2003; Romano et al. 2002).

In this paper we present the results of a 37 ks observation of 2MASX J21362313−6224008, a Seyfert 1 galaxy with a measured redshift \( z = 0.0588 \) (Hewitt & Burbidge 1991) and visual magnitude \( V = 15.2 \text{ mag} \) (Remillard et al. 1986), with the Far Ultraviolet Spectroscopic Explorer (FUSE). The available X-ray HEAO-1 data of the source (also identified as 1H 2129−624 and H2132−626) were analyzed by Remillard et al. (1986), who derive a luminosity \( L_{2−10\text{ keV}} = 3 \times 10^{44} \text{ ergs s}^{-1} \), which is on the bright end of the quasar luminosity function (George et al. 2000). The object was observed in soft X-rays by ROSAT; the ROSAT All Sky Bright Source Catalogue (Voges et al. 1999) and the ROSAT Bright Survey (Schwope et al. 2000) detect a strong X-ray source at the location of our target, which is identified as 1RXS J213623.1−622400. (Its quoted X-ray flux may be contaminated by up to 10% by the faint source 1RXS J213530.1−623005 approximately 12′ to the southwest.) The Extreme Ultraviolet Explorer (EUV) observed the source during its All Sky Survey, but the short exposure time resulted only in an upper limit (Marshall et al. 1995). The spectral energy distribution (SED) of 2MASX J21362313−6224008 is shown in Figure 1.

2. OBSERVATIONS AND DATA REDUCTION

FUSE consists of four separate optical systems. Two employ LiF coatings and are sensitive to wavelengths from 990 to 1187 Å, while the other two use SiC coatings, which provide reflectivity to wavelengths as short as 905 Å. The four channels overlap between 990 and 1070 Å. For a complete description of the instrument, see Moos et al. (2000) and Sahnow et al. (2000).

The FUSE spectrum of 2MASX J21362313−6224008 (data set D9030401) was obtained in 10 separate exposures on 2003 May 25−26. The total integration time was 37 ks, of which 12 ks were obtained during orbital night. All observations were made through the 30′′ low-resolution (LWRS) aperture. The data were reduced using version 2.4 of the CalFUSE calibration software pipeline, described in the CalFUSE Pipeline Reference Guide (Dixon et al. 2003), but with the following modification: the first half of the pipeline, which corrects for time-dependent effects (such as spacecraft jitter), was run separately on each exposure. The resulting position-corrected photon event lists were combined, using the program TTAG_COMBINE, into a single data file. The second half of the pipeline, which performs background subtraction and spectral extraction (among other tasks), was run on the combined data file. By thus using the entire data set to scale the background model, we optimize its fidelity, an important consideration for faint continuum sources.

The FUSE flux calibration, based on theoretical models of white dwarf stellar atmospheres, is believed to be accurate to about 10% (Sahnow et al. 2000). Error bars are assigned to the data assuming Gaussian statistics. To increase their signal-to-noise ratio, we bin the spectra by 4 detector pixels, about half of a resolution element. The far-ultraviolet spectrum of 2MASX J21362313−6224008 (Fig. 2) shows a power-law continuum with a broad O vi emission feature at the redshift of the AGN. Selected spectral regions showing redshifted absorption features are presented in Figure 3.

1 Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer. FUSE is operated for NASA by the Johns Hopkins University under NASA contract NAS 5-32985.
3. SPECTRAL ANALYSIS

Because the four channels are essentially independent spectrographs, they have different line-spread functions, and their data cannot be safely combined into a single spectrum. Instead, we use only the spectrum from the channel with the highest sensitivity at the wavelength of interest. We identify statistically significant absorption features with a simple routine that bins each spectrum to the instrument resolution and flags regions whose flux lies more than $3\sigma$ below the local median. Most of these features are due to the interstellar medium (ISM) of our Galaxy, but a handful share the redshift of the AGN: Ly$\gamma$, C$\text{III}$, Ly$\alpha$, O$\text{VI}$, and C$\text{II}$ (Fig. 3).

Absorption-line profiles are modeled with the interstellar line-fitting package written by M. Hurwitz and V. Saba. Wavelengths, oscillator strengths, and other atomic data are taken from Morton (1991). Given a column density and Doppler broadening parameter, the program computes a Voigt profile for each absorption feature and produces a high-resolution ($0.001\,\text{Å}$) spectrum of $\tau$ versus wavelength. The model spectra are convolved with a Gaussian of FWHM = 0.08 Å, roughly the spectral resolution of our data, and rebinned to 0.01 Å.

Model spectra are fitted to the data using the nonlinear curve-fitting program SPECFIT (Kriss 1994), which runs in the IRAF environment. SPECFIT performs a $\chi^2$ minimization of the model parameters. Error bars for a particular parameter are derived by fixing that parameter at the best-fit value, then raising it, allowing the other model parameters to vary freely, until $\chi^2$ is increased by 1, which corresponds to a 1 $\sigma$ deviation for a single interesting parameter (Avni 1976).

We begin with the segment of the LiF 1A spectrum shown in the top panel of Figure 3, which includes the redshifted Ly$\gamma$, Ly$\alpha$, C$\text{III}$, and O$\text{VI}$ emission. Most absorption lines are due to the ISM of our Galaxy.
absorption at two velocities. Comparison with data taken during orbital night (not shown) indicates that Ly\textgamma is well separated from the geocoronal O i \lambda 1028 emission line. The redder O vi \lambda 1038 line is contaminated by J = 1 H2 absorption. Assuming a linear continuum over the wavelength region 1028.4–1038.6 Å, we model all nine species/velocity components labeled in Figure 3. We constrain the depth of the H2 line by fitting two other J = 1 H2 lines in the 1049–1052 Å range simultaneously. Derived parameters for the Galactic O vi lines are presented in Table 1 and those for the redshifted features in Table 2.

To model the redshifted Ly\beta \lambda 1026 feature, we use data from the SiC 1A channel (Fig. 3, middle panel), as the more sensitive LiF channels do not include this emission range. The Ly\beta line falls between a pair of geocoronal emission features due to N ii * \lambda\lambda 1084.6, 1085.7. The pair of N ii \lambda 1084 absorption features is interstellar. A comparison with the night-only spectrum (not shown) indicates that N ii * \lambda 1084.6 does not contribute significantly to this spectrum and that the narrow peak on the blue shoulder of the N ii * \lambda 1085.7 line is probably not geocoronal but intrinsic to the target spectrum. Diffuse emission filling the LWRS aperture yields a line profile that is well approximated by a top-hat target relative to the center of the LWRS aperture can lead to a zero-point uncertainty in the final digits of the redshift. In col. (2), the digits in parentheses represent the 1 σ uncertainty in the final digits of the redshift. In col. (3), velocities are quoted relative to the systemic velocity of 2MASX J21362313–6224008 (\textit{cz} = 0.0588 and \textit{cz} = 17,630 km s\(^{-1}\)).

### Table 1

| Velocity (km s\(^{-1}\)) | Doppler Parameter (km s\(^{-1}\)) | Column Density log N (cm\(^{-2}\)) |
|--------------------------|-----------------------------------|------------------------------------|
| 27 ± 3.................... | 53 ± 6                            | 14.44 ± 0.03                       |
| 175 ± 6.................... | 26 ± 15                           | 13.77 ± 0.09                       |

**Note.**—Velocities are quoted relative to the local standard of rest (LSR; Mihalas & Binney 1981).

### Table 2

| Feature | Redshift (1) | Velocity (km s\(^{-1}\)) (2) | Doppler Parameter (km s\(^{-1}\)) (3) | Column Density log N (cm\(^{-2}\)) (5) |
|---------|--------------|-------------------------------|--------------------------------------|--------------------------------------|
| Ly\gamma \lambda 972.5............................... | 0.05776(7) | \(-312 ± 2\)                  | 27 ± 5                              | 14.97 ± 0.05                       |
| C iii \lambda 977.0................................. | 0.05778(35) | \(-305 ± 1\)                  | 24 ± 3                              | 13.95 ± 0.06                       |
| Ly\beta \lambda 1025.7.............................. | 0.05777(015) | \(-309 ± 3\)                  | 26 ± 9                              | 14.89 ± 0.14                       |
| O vi \lambda\lambda 1031.9, 1037.6,............. | 0.05778(39) | \(-305 ± 3\)                  | 20 ± 2                              | 13.95 ± 0.05                       |
| C ii \lambda 1036.4............................... | 0.05776(087) | \(-312 ± 3\)                  | 6 ± 10                              | 13.45 ± 0.16                       |

**Note.**—In col. (2), the digits in parentheses represent the 1 σ uncertainty in the final digits of the redshift. In col. (3), velocities are quoted relative to the systemic velocity of 2MASX J21362313–6224008 (\textit{cz} = 0.0588 and \textit{cz} = 17,630 km s\(^{-1}\)).
profiles. Our target is similar to NGC 3783 in that broad emission from Ly$\beta$ and higher order Lyman lines is negligible (Gabel et al. 2003).

4. DISCUSSION

Derived parameters for the Galactic O vi lines are presented in Table 1, and those for the redshifted features are presented in Table 2. The Ly$\beta$ and $\gamma$ lines yield consistent values for the redshifted H$\alpha$ column density and Doppler parameter $b$. We adopt a value of $N(\text{H} \alpha) = 10^{15}$ cm$^{-2}$ in our analysis.

4.1. Photoionization Modeling

The redshifted H$\alpha$, C$\alpha$, C$\beta$, and O vi lines indicate the presence of ionized gas in the neighborhood of the AGN (e.g., Crenshaw et al. 1999) moving away from the central source with a speed of $\sim 310$ km s$^{-1}$ (Table 2). Photoionization models can be used to constrain the parameters of the absorbing gas. We use CLOUDY version 94 (Ferland 1996) to calculate the fractional abundance $f_{\text{ion}}$ of an element in a given ionization state, assuming the illuminating continuum described by the CLOUDY “table agn” model, an absorbing gas with solar abundances, total hydrogen density $n(\text{H}) = 10^5$ cm$^{-3}$, and a grid of values for the total hydrogen column density $N_{\text{H}}$ and ionization parameter $U$. The measured SED of 2MASX J21362313$-$6224008 (Fig. 1) is consistent with the table agn model employed in the calculation; other studies (e.g., Romano et al. 2002) indicate that the use of other SEDs for the illuminating spectrum result in only minor changes to the derived values of $N_{\text{H}}$ and $U$. We compare the column densities $N_{\text{ion}}$ presented in Table 2 with the predictions of the photoionization model to constrain $U$ and $N_{\text{H}}$ in the absorbing gas.

In §3, the covering fraction of the absorbing gas in 2MASX J21362313$-$6224008 was found to be $0.5 \leq C_f \leq 1.0$, consistent with most other intrinsic UV absorbers in AGNs (Crenshaw et al. 1999). Following Arav et al. (2001) and Romano et al. (2002), we plot curves of constant $N_{\text{ion}}$ in the log($U$)-log($N_{\text{H}}$) plane in Figure 4. If the absorbing gas covers only part of the emitting region, then $N_{\text{ion}}$ is a lower limit and the allowed region of parameter space lies above all the curves in Figure 4 (see Arav et al. 2001 for details). The total hydrogen column density of warm absorbers in Seyfert galaxies is usually lower than $10^{21}$ cm$^{-2}$ (Kriss et al. 2000, 2003; Romano et al. 2002; Blustin et al. 2003). Given the constraints of Figure 4, we tentatively place the UV absorber at log ($U$) = $-2$, log ($N_{\text{H}}$) = 20, keeping in mind that substantially higher column densities are not excluded by our data. Observations of other UV, optical, or X-ray lines are required to further constrain the state of the absorber in this AGN.

If the absorption is due to multiple velocity components, the assumption of a single, uniform cloud breaks down, and this model is not applicable.

4.2. Physical Condition of the Warm Absorber

The ionization parameter is defined as $U = Q(\text{H})/4\pi r_0^2 n(\text{H})c$, where $Q(\text{H})$ is the number of ionizing photons ($E \geq 1$ ryd), $n(\text{H})$ is the total hydrogen number density, $c$ is the speed of light, and $r_0$ is the distance of the illuminated face of the cloud from the central source. We use the measured 2–10 keV luminosity $(3 \times 10^{44}$ erg s$^{-1})$ in conjunction with the assumed table agn SED to derive a flux of $Q(\text{H}) = 10^{45}$ s$^{-1}$ ionizing photons for 2MASX J21362313$-$6224008.

Knowing $U$, $N_{\text{H}}$, and the density $n(\text{H})$, one can derive the distance, size, and mass of the absorbing cloud. Our data provide no constraints on the density of the absorber variability studies or other information such as imaging data are necessary to measure $n(\text{H})$ (e.g., Hamann et al. 1997b; Crenshaw et al. 2002)—so we will continue to use the value $n(\text{H}) = 10^5$ cm$^{-3}$ assumed by the table agn model. Adopting the “best-guess” values of log ($U$) = $-2$, log ($N_{\text{H}}$) = 20 derived above, we find that the illuminated face of the absorber lies $r_0 = 160 U_{-2}^{-1/2} n_{10}^{-1/2} N_{20} M_{50}$ pc from the central source. The size of the absorbing cloud is simply given by $L = N_{20} n_{10} \text{H}(\text{H}) = 10 N_{10} n_{10} h^{-2} M_{50} \text{pc}$. Since $L \ll r_0$ for a wide range of hydrogen densities $n(\text{H})$, the volume of the warm gas can be approximated as $V = 4\pi r_0^2 L C_f$, and the mass of the warm absorber is

$$M \sim 2.1 \times 10^7 U_{-2}^{-1} n_{10}^{-1} N_{20} C_f M_{50}.$$

4.3. An Intergalactic Origin for the Absorption Lines?

The line of sight to 2MASX J21362313$-$6224008 intersects several clusters of galaxies, two of which have measured redshifts: A3782 at $z = 0.0557$ and APMCC 684 at $z = 0.056$. The difference in redshift between the measured absorption lines ($z \sim 0.0578$) and the two clusters is so small that an alternative interpretation of the absorption lines can be entertained, viz., the source shines through the foreground cluster(s), which causes the redshifted absorption lines.

The center of A3782 lies $\sim 26'$ from 2MASX J21362313$-$6224008, which corresponds to approximately 1.8 Mpc (for a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$). The center of APMCC 684 is $\sim 17'$ distant, which corresponds to 1.2 Mpc. Clusters of galaxies are known to host hot intergalactic gas ($T \geq 10^7$ K)—too hot to produce the observed absorption lines—and sometimes a lower temperature phase ($T \sim 10^5$–$10^6$ K; Lieu et al. 1996a, 1996b; Bonamente et al. 2002, 2003) that could contain substantial amounts of O vi, C ii, C iii,
and neutral atomic hydrogen. This warm intergalactic gas has been observed in emission in several clusters (i.e., the “soft excess” phenomenon; Bonamente et al. 2002; Ka distra et al. 2003; Nevalainen et al. 2003), notably in the Coma cluster, where it extends some 2.6 Mpc from the cluster center (Bonamente et al. 2003). Detection of O vi absorption associated with the Local Group of galaxies has been recently reported by Nicastro et al. (2003), and detection of an O vi absorption system associated with another galaxy group was reported by Tripp & Savage (2000). Here we investigate the association of the detected absorption systems with the two galaxy clusters A3782 and APMCC 684.

We use the soft excess measurements of Bonamente et al. (2003) for the Coma cluster to estimate the amount of low-ionization gas in clusters of galaxies. Several other clusters contain warm gas in amounts comparable (within a factor of a few) to those of the Coma cluster. The warm gas is generally more diffuse than the hot gas (Bonamente et al. 2002), and it could reside either inside the cluster (i.e., mixed with the hot gas) or in filamentary structures outside the cluster, as is often seen in hydrodynamic simulations (e.g., Cen & Ostriker 1999). If the warm gas is bound to the cluster, Bonamente et al. (2003) show that it must have a density of $1.5 \times 10^{-3} - 6 \times 10^{-5}$ cm$^{-3}$ throughout the cluster. Assuming a cluster radius of $\sim 3$ Mpc, in agreement with current X-ray measurements, this density implies H i column densities of $\sim 10^{20}-10^{22}$ cm$^{-2}$. The metal abundance of the warm gas is $\sim 0.1$ solar (Bonamente et al. 2003); this implies total carbon column densities of $N_{C} \sim 5 \times 10^{15}-5 \times 10^{17}$ cm$^{-2}$ and oxygen column densities of $N_{O} \sim 10^{16}-10^{18}$ cm$^{-2}$. Figure 5 shows the ionization fractions of the ions of concern as a function of temperature, assuming ionization equilibrium (Mazzotta et al. 1998). Column densities of H i, C ii, C iii, and O vi predicted by this scenario are therefore consistent, for a wide range of temperatures, with those detected toward 2MASX J21362313 – 6224008 (Table 2). The warm gas may alternatively reside in filamentary structures with densities of $\sim 10^{-4}-10^{-6}$ cm$^{-3}$ (Davé et al. 2001). In this case, Bonamente et al. (2003) show that the filaments will extend for $\sim 10$ Mpc outside the cluster, yielding similar ion column densities. In addition, the Doppler parameters b of a warm gas at $T \sim 10^{4}-10^{6}$ K are fully consistent with the values derived in Table 2 (Spitz er 1978) and similar to those of Tripp & Savage (2000).

We conclude that the current data for 2MASX J21362313 – 6224008 are consistent with the redshifted absorption lines of Table 2 originating from warm gas associated with an intervening galaxy cluster.

5. CONCLUSIONS

We detect Galactic O vi absorption in the direction of 2MASX J21362313 – 6224008 and H i Ly$\beta$ and $\gamma$, C ii, C iii, and O vi absorption at a redshift of $z \sim 0.0578$. The redshifted absorption lines are consistent with a circumnuclear absorber outflowing with a relative velocity of $-310$ km s$^{-1}$. We derive constraints on its physical parameters through photoionization modeling. Alternatively, we suggest that the redshifted absorption may originate in or around a cluster of galaxies located along the line of sight.

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REFERENCES

Arav, N., et al. 2001, ApJ, 561, 118
Avni, Y. 1976, ApJ, 210, 642
Blustin, A. J., et al. 2003, A&A, 403, 481
Bonamente, M., Joy, M. K., & Lieu, R. 2003, ApJ, 585, 722
Bonamente, M., Lieu, R., Joy, M. K., & Nevalainen, J. 2002, ApJ, 576, 688
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Crenshaw, D. M., Kraemer, S. B., Boggess, A., Maran, S. P., Mushotzky, R. F., & Wu, C. 1999, ApJ, 516, 750
Crenshaw, D. M., et al. 2002, ApJ, 566, 187
Davé, R., et al. 2001, ApJ, 552, 473
Dixon, W. V., Kruk, J. W., & Murphy, E. M. 2003, The CalFUSE Pipeline Reference Guide (Baltimore: Johns Hopkins), http://fuse.pha.jhu.edu/analysis/pipeline_reference.html
Ferland, G. J. 1996, Hazy: A Brief Introduction to CLOUDY (Univ. Kentucky Dept. Phys. Astron. Int. Rep.)
Gabel, J. R., et al. 2003, ApJ, 583, 178
George, I. M., Turner, T. J., Yaqoob, T., Netzer, H., Laor, A., Mushotzky, R. F., Nandra, K., & Takahashi, T. 2000, ApJ, 531, 52
Hamann, F., Barlow, T. A., & Junkkarinen, V. 1997a, ApJ, 478, 87
Hamann, F., Barlow, T. A., Junkkarinen, V., & Burbidge, E. M. 1997b, ApJ, 478, 80
Hewitt, A., & Burbidge, G. 1991, ApJS, 75, 297
Kaastra, J. S., Lieu, R., Tamura, T., Pae r eils, F. B. S., & den Herder, J. W. 2003, A&A, 397, 445
Kriss, G. A. 1994, in ASP Conf. Ser. 61, Astronomical Data Analysis Software and Systems III, ed. D. R. Crabtree, R. J. Hanisch, & J. Barnes (San Francisco: ASP), 437
Kriss, G. A., Blustin, A., Branduardi-Raymont, G., Green, R. F., Hutchings, J., & Kaiser, M. E. 2003, A&A, 403, 473
Kriss, G. A., et al. 2000, ApJ, 538, L17
Lieu, R., Mintz, J. P. D., Bowyer, S., Breen, J. O., Lockman, F. J., Murphy, E. M., & Hwang, C.-Y. 1996a, Science, 274, 1335
