Extreme Ultraviolet Spectroscopy of the Seyfert 1 Galaxy Markarian 478

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The Seyfert 1 galaxy Mrk 478, observed during the *EUVE* all-sky survey, is the brightest EUV source among its class. The SW spectrum of this object shows evidence of discrete emission, although this interpretation is tentative, since the source spectrum must be extracted against a bright background. If the EUV flux is, in fact, composed partly of line emission, we consider the implications if this is the result of emission from a collision-driven plasma at temperatures $\gtrsim 10^6$ K. In this context, we discuss some of the constraints imposed on the emission-line region by this observation.

1. Introduction

The opportunity to make high spectral resolution measurements of the spectra of active galactic nuclei (AGN) in the EUV has been made possible by the launch of the *Extreme Ultraviolet Explorer* (*EUVE*; Bowyer & Malina 1991). Those few AGN whose EUV fluxes are observable after attenuation by the interstellar medium (the neutral H column cannot greatly exceed 10^{20} cm^{-2}) are tempting targets for direct study of the blue bump, the broad UV/EUV peak in νL_ν.

Current models of the energy production mechanisms in AGN typically involve accretion onto supermassive black holes (Rees 1984), thereby requiring the presence of large quantities of fueling matter in a compact region. The distribution of this matter is an unsettled issue; it has long been expected that a disk, which then plays a key role in its capacity to transport angular momentum and to efficiently convert energy, describes the distribution near the black hole. The characteristic radiation temperature near the last stable orbit in the Schwarzschild potential is given by

$$T_C = 4.9 \times 10^5 \, M_7^{-1/4} \left(\frac{L}{L_E}\right)^{1/4} \left(\frac{\eta}{0.1}\right)^{-1/4} \mathrm{K}, \tag{1.1}$$

where L_E is the Eddington luminosity and M_7 is the central mass in units of 10^7 M$_\odot$. The accretion efficiency, η, is defined by $L = \eta \dot{M} c^2$, where L is the accretion-driven luminosity and $\dot{M}$ is the accretion rate. Because of the weak dependence of T_C on M, a wide range of central masses should produce a peak in the EUV band.

The existence of an EUV peak does not, however, unequivocally imply an accretion disk origin. Guilbert & Rees (1988) show that an EUV excess can arise even if the primary spectrum is purely non- thermal, produced, for example, by $e^+ - e^-$ annihilation (e.g., Zdziarski et al. 1990). Some fraction of the emitted radiation must be intercepted by matter with high Compton depth that subsequently re-emits this energy in the form of a blackbody spectrum. Assuming that such optically thick matter exists, we can estimate the resulting blackbody temperature. In terms of the Schwarzschild radius R_S, it is

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approximately

$$T_{BB} = 6.7 \times 10^5 \, \phi^{1/4} M_7^{-1/4} (1-a)^{1/4} \left(\frac{L}{L_E}\right)^{1/4} \left(\frac{R}{R_S}\right)^{-1/2} \mathrm{K}, \tag{1.2}$$

for a cloud with albedo a at a distance R from the primary radiation source. The quantity ϕ is the ratio of the area of an individual cloud, projected along its line of sight to the central radiation source, to the total surface area. Therefore, if the clouds are in the vicinity of the primary radiation source, the blackbody spectrum can peak in the EUV range, provided that the accretion rate is not negligible compared to the Eddington limit.

Barvainis (1993) has suggested a model in which the blue bump arises from an optically thin thermal bremsstrahlung continuum. In the EUV band, the emission from a plasma in the temperature range $10^5 - 10^7$ K is entirely dominated by line emission (e.g., Mewe, Gronenschild, & van den Oord 1985), so that any quantitative arguments concerning the feasibility of this model for producing the EUV bump must consider discrete line emission, not just continuum emission. Evidence in the form of discrete emission (e.g., Ne VIII [Hamann, Zuo, & Tytler 1995; Kaastra, Roos, & Mewe 1995*ab*]) or continuum absorption (e.g., O VII [Nandra & Pounds 1992]) for the existence of a substantial circumnuclear plasma capable of supporting "warm" gas is beginning to accumulate. We note, however, that in none of the three cases discussed above does line emission enter into the arguments presented to date.

Among the AGN significantly detected during the *EUVE* all-sky survey, Mrk 478 is the second brightest Seyfert galaxy (Bowyer et al. 1995). Observations of Mrk 478 and a preliminary analysis of the spectral data are described in the next section. We find that the spectrum is consistent with discrete emission from a plasma with a temperature near 10^6 K. In § 3, we discuss some of the constraints and problems that accompany the existence of line emission in this band.

2. Observations and Data Analysis

Mrk 478 was observed with *EUVE* over the period 1993, April 9–18, for 303,000 s effective exposure time. Part of the observation (152,000 s exposure) was conducted with the source positioned off the optical axis of the Spectrometer Telescope, along the dispersion direction of the short-wavelength spectrometer, in an effort to extend the sensitivity of the instrument to shorter wavelengths.

The off-axis data were aspect corrected to the nominal on-axis position, and both datasets were reduced separately. For each image, we located the spectral image on the detector, and positioned a slightly curved mask of width 21 pixels on the spectrum along the dispersion direction; the mask curves with the spectrum. The count spectrum is obtained by integrating over the mask in the cross-dispersion direction. Next, we positioned background extraction regions above and below the spectral image. The width of these boxes was 84 pixels in the cross-dispersion direction; we verified that the background subtraction was insensitive to the actual width of the background regions. The total net source counts over the wavelength band 72–120 Å, after background subtraction, are 1093 ± 162, and 747 ± 138 for the on-axis and off-axis observations, respectively. In the final step, pixel numbers were converted to wavelength, and the observed count spectrum was divided by the effective area of the spectrometer to obtain the physical fluxes. This introduces an uncertainty, because of the unknown correction to the spectrometer effective area for off-axis position; but since statistical fluctuations dominate, this is probably a small effect. We summed both spectra in order to improve the signal-to-noise ratio.

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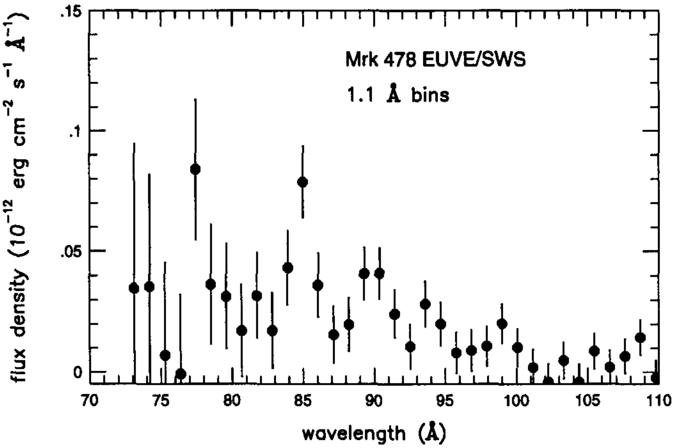

FIGURE 1. Average spectrum of Mrk478 observed with *EUVE* in April, 1993. The spectrum has been background subtracted, and is binned in 1.1 Å bins. Note the presence of discrete structure near 78, 85, and 90 Å, suggestive of emission line complexes.

The total summed spectrum, binned in 1.1 Å bins (16 pixels) is shown in Figure 1. The source is significantly detected over the 76–110 Å band and shows obvious structure.

We used a simple power law with interstellar absorption by cold gas, with slope and normalization determined with the *ROSAT* PSPC (Gondhalekar et al. 1994). This assumption is justified by the fact that the source has shown little X-ray spectral variability in the past. This assumed continuum reproduces the average flux densities as a function of wavelength reasonably well.

3. Interpretation of the Discrete Structure

The EUV spectrum in the spectral range corresponding to the SW bandpass is dominated by $2s - 2p$ intrashell emission from highly ionized Fe (more ionized than Fe^{16+}) if the electron temperature exceeds 3×10^6 K. We can easily rule out a high-temperature plasma as the source of EUV line emission, since, for example, we would not expect strong emission near 85 Å (79 Å in the rest frame; $z = 0.079$) for $T \gtrsim 10^{6.4}$ K. At temperatures nearer 10^6 K, the spectrum can be extremely complicated, consisting of L-shell emission from Ne, Mg, and Si, and Fe M-shell emission. These ions can also be important sources of line emission in a photoionized plasma, although the corresponding electron temperatures are roughly an order of magnitude lower. With lower temperatures, the ionic spectra can be markedly different because of the dominance of recombination in populating excited states. Theoretical spectra from these ions are poorly understood at this time. We are in the process of calculating these spectra in detail (Liedahl, Osterheld, & Goldstein 1995). Our analysis is still preliminary, but our calculated spectra of a photoionized plasma appear to be qualitatively incompatible with the observed spectra.

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Therefore, we investigate the consequences of interpreting the spectra in terms of line emission from a plasma in collisional equilibrium.

The volume emission measure for a thin ($\Delta R << R$) spherical shell is given by $EM = 4\pi R^2 \Delta R n_e^2$. If we hypothesize that the complex near 85 Å is a blend of emission from Fe XII and Fe XIII plasma, then $EM \approx 10^{67}$ cm^{-3} for standard cosmic abundances (Allen 1973). We assume an electron temperature of $10^{6.2}$ K, the temperature at which the Fe charge state distribution is dominated by $Fe^{(11-13)+}$ (Arnaud & Raymond 1992).

Marshall et al. (1995) show that the SW flux can vary by a factor of two over approximately 0.5 d. If we assume that the varying flux includes the line emission, then the extent of the emission-line region, projected along our line of sight, D, is constrained by $D \lesssim ct_{\rm var}$, where $t_{\rm var}$ is the factor-of-two flux variation timescale. With spherical symmetry, we have $R \lesssim 1.3 \times 10^{15}$ cm.

If the lines are to originate in a plasma that is dominated by electron impact ionization, rather than by photoionization, then $n_e C > \beta$, where C is the collisional ionization rate coefficient, and β is the photoionization rate. For an estimate of the constraint imposed by this requirement, take $C = 6 \times 10^{11}$ cm^3 s^{-1} as a representative collisional ionization rate coefficient for an Fe M-shell ion in coronal equilibrium (Arnaud & Raymond 1992), and $\beta = 1.2 \times 10^3 \ R_{15}^{-2}$ s^{-1}, using the power-law spectrum given in Gondhalekar et al. (1994). The average radius of the shell is given in units of 10^{15} cm and is denoted by R_{15}. This provides a relationship between R and n_e. In fact, it provides the strictest constraint on the density: $n_e \gtrsim 1.2 \times 10^{13}$ cm^{-3}, where we have taken $R_{15} = 1.3$.

To check the consistency of the thin-shell assumption, use the relation $\Delta R/R = EM/4\pi R^3 n^2$. Using the most liberal constraints (maximum allowed radius and minimum allowed density), $\Delta R/R = 3 \times 10^{-6}$, which, though consistent, seems unlikely in the context of a shell distribution. Keep in mind, however, that this 'model' is simply a device to allow us to begin studying the plausibility of a relatively compact source of line emission in Mrk 478.

As noted by Elvis et al. (1991), the rapid time variations in AGN spectra often imply an optically thick emission region (cf., Barvainis 1993). We can estimate the possible effects of Compton scattering and resonant scattering. Let σ_T and τ_T denote the Thomson cross-section and the electron scattering optical depth, respectively. With $EM = 4\pi R^2 n_e \tau_T \ \sigma_T^{-1}$, $R = 1.3 \times 10^{15}$ cm, and $n_e = 1.2 \times 10^{13}$ cm^{-3}, we find a scattering depth of 3×10^{-2}, which is safely less than unity for a range of allowed parameters.

As an example of the effect of resonant scattering, consider an Fe ion, with elemental abundance $A_{\rm Fe}$, ionic fraction $F_{\rm ion}$, a fractional level population in the lower state of the transition $\Phi_{\rm lev}$, and an oscillator strength f. By eliminating ΔR in favor of EM, the line-center optical depth is given by

$$\tau_o = \frac{\pi^{1/2} e^2}{m_e c^2} A_{\rm Fe} F_{\rm ion} \Phi_{\rm lev} \left(\frac{n_H}{n_e}\right) \frac{EM}{4\pi R^2 n_e} \left(\frac{m_{\rm Fe} c^2}{2kT}\right)^{1/2} f\lambda, \tag{3.3}$$

where the remaining quantities have their conventional meaning. Numerically, this is

$$\tau_o = 2.1 \times 10^3 \ F_{\rm ion} \Phi_{\rm lev} (EM)_{67} R_{15}^{-2} (n_e)_{13}^{-1} \left(\frac{\lambda}{100 \text{ Å}}\right) \left(\frac{f}{0.1}\right) \left(\frac{kT}{100 \text{ eV}}\right)^{-1/2}. \tag{3.4}$$

Although this appears to be rather high, the escape of photons is still possible because the factor $\Phi_{\rm lev}$ is less than 10^{-4} for the vast majority of transitions in the intermediate Fe M-shell ions (e.g., Fe XII, Fe XIII), which drops τ_o below unity. For example, this is the case for all levels above the 4th excited state in Fe^{12+}, which emits a complex of lines near 79 Å in its rest frame.

At a temperature of $10^{6.2}$ K, the dominant oxygen charge state is He-like, with a K

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photoionization edge at 739 eV. If we use the same emission measure as above, we find that the edge optical depth in O^{6+} is $\tau_{oxy} \approx 50\ (EM)_{67} R_{15}^{-2} (n_e)_{13}^{-1}$. Although the O^{6+} zone is transparent to the EUV lines, it is opaque to the X-ray continuum above 0.74 keV. Therefore, in light of the *ROSAT* spectrum, the EUV line-emitting material cannot entirely occult the X-ray continuum source. However, this does not seriously affect the above analysis, since modifications of the above equations with $4\pi \rightarrow \Omega < 4\pi$ can be tolerated.

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