We present a method for isolating the spectrum of the geocoronal emission lines observed with the FOS which takes advantage of the fact that the geocoronal flux varies regularly over the orbit of the spacecraft. We also describe a model for the profiles of the geocoronal lines which is based on the characteristics of the spectrograph. The model profiles are compared with observations and they are found to be in good agreement. In the case of observations carried out through a large aperture (e.g., the 4"3 square aperture) the geocoronal lines are so broad that they form a pedestal under the intrinsic emission lines from the target of the observation. Under these circumstances, knowledge of the profiles of the geocoronal lines allows one to subtract them successfully. However, for observations made through the 0"86 apertures (circular or rectangular) the width of the geocoronal Lyα line is likely to be comparable to the intrinsic width of the line from the target of the observation.

1. Introduction

A well known problem associated with the analysis and interpretation of UV spectra of astronomical objects (especially Galactic ones) is the contamination of their spectra by geocoronal emission lines. In particular the geocoronal Lyα line is a prominent line which often overwhelms the intrinsic Lyα line from the target of the observation. In this report we describe an empirical method for obtaining the profiles of geocoronal emission lines in the spectra of objects observed with the FOS in RAPID mode. This method takes advantage of the fact that the flux of the geocoronal lines varies regularly over the orbit of the spacecraft. In addition to the empirical method we describe a model for the line profiles which is based on the characteristics of the spectrograph. The profiles of the geocoronal lines are an essential ingredient in any scheme for subtracting them from the observed spectra. In §2 we concentrate on obtaining the observed profiles of the geocoronal Lyα and O i λ1304 lines using the spectrum of a quasar and time-resolved spectra of a cataclysmic variable. We use the observed geocoronal spectrum in §3 to assess the applicability of our proposed model for the line profiles from a large rectangular aperture. In §4 we model the profiles of the geocoronal lines observed through a small aperture (circular or square), for which the method is somewhat different than in the previous example. We compare the model profiles from this case with the geocoronal Lyα profile observed in the spectrum of an active galactic nucleus whose intrinsic Lyα line is redshifted away from the geocoronal line and with the spectrum of a supernova remnant whose intrinsic Lyα line is weak.

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The geocoronal Lyα and O I lines are encountered only in the shortest wavelength spectra obtained on the BLUE side of the FOS. In particular, there are two gratings which can cover these lines in 1st order: the G130H and the G160L. For the purposes of this study we use observations of four objects, which were taken through apertures of different sizes: pre-COSTAR observations of the cataclysmic variable AE Aquarii taken in RAPID mode, and the supernova remnant N49 taken in ACCUM mode, and post-COSTAR observations of the quasar 4C 73.18 (z=0.302) and of the broad-line radio galaxy Arp 102B (z=0.0244), both taken in ACCUM mode. In addition we make limited use of an observation of the cataclysmic variable DQ Herculis taken in RAPID mode to verify the conclusions drawn from the AE Aquarii observation about the variability of the geocoronal lines. Table 1 gives a summary of the instrument configuration during the observations and the dataset names.

2. Variability of Geocoronal Lines and Their Observed Profiles

The simplest way to isolate the a geocoronal emission line profile is to look in the spectrum of a quasar where the intrinsic Lyα line is redshifted. A good example is afforded by 4C 73.18, whose intrinsic Lyα line is redshifted to 1583 Å, far away from the geocoronal line, and which was observed through the (large) 4′3 aperture. Figure 1 shows the profile of the geocoronal Lyα line as observed in the spectrum of 4C 73.18. The profile of the count rate spectrum is compared to the profile of the flux spectrum. In the former spectrum the line profile is flat-topped since the geocoronal emission fills the aperture uniformly and the profile is formed by the projection of the aperture onto the detector array. The latter profile is the product of the former with the inverse sensitivity function (also shown), and as a result it is skewed. This feature of the line profile is an important clue which can help in the development of a model for it, as we describe in the next section.

If the target of the observation is a star, the geocoronal Lyα line unfortunately overlaps with the intrinsic line from the star. To isolate the profiles of the geocoronal lines in this particular
case, and construct their light curve we take advantage of two characteristic properties which they possess:

1. Because geocoronal emission is diffuse and fills the spectrograph aperture, the geocoronal lines can be much broader than the intrinsic lines from the target object. In the particular case of the AE Aqr observation the aperture is 4.3 wide, which corresponds to a width of 12 diodes or 24 pixels (∼80 Å) when projected onto the detector array. This is illustrated in Figure 2 which shows an enlarged segment of the spectrum of AE Aqr with the geocoronal lines identified.

2. The flux of the geocoronal lines varies over the orbit of the spacecraft, according to the spacecraft’s position in the Earth’s magnetic field. This variability is approximately periodic over a few spacecraft orbits, and it is different from any variability of the target of the observation itself. This is illustrated in Figure 3 where the light curve of the geocoronal Lyα during the observation of AE Aqr is compared to the light curve of the star. The light curve of the star depicts the behavior of the 2000–2200 Å continuum, which is not affected by geocoronal emission. The geocoronal Lyα light curve shows the variations of the blue side of the line, which does not include any contribution from the intrinsic Lyα line from the star. The geocornal Lyα flux in the observation of DQ Her behaves in the same way over the orbit of the spacecraft, as it does in the observation of AE Aqr.

The behavior seen in the light curves can be exploited, regardless of its physical origin, in developing a scheme for decomposing the observed spectrum into flaring (i.e., variable) and quiescent (i.e., constant) emission from the star plus geocoronal emission. In particular, we make the assumption that the flux density at any point in the spectrum can be regarded as a linear combination of three components, as follows: a constant, a component which varies proportionally to the star’s continuum flux, and a component which varies proportionally to the flux of the blue side of the geocoronal Lyα line. This assumption is justified by the light curve presented here and by the analysis of Eracleous & Horne (1996). The third component is the spectrum of the geocoronal emission modulo a scale factor. The linear decomposition can be cast mathematically as

\[ f_\nu(\lambda, t) = C_\nu(\lambda) + S(\lambda) F_\nu(t) + G(\lambda) \tilde{\phi}_\nu(t), \]  

In this equation \( C_\nu(\lambda) \) is the spectrum of the constant component, \( S(\lambda) \) is the spectrum of the varying component of the star’s light, and \( G(\lambda) \) is the spectrum of the geocoronal emission. The light curve of the star is denoted by \( F_\nu(t) \), while \( \tilde{\phi}_\nu(t) \) is the geocoronal Lyα light curve. Although \( \lambda \) denotes the wavelength, in principle, it can also be regarded as a label for discrete pixels in the spectrum. The three spectral components \( C_\nu(\lambda), S(\lambda), \) and \( G(\lambda) \), are determined by a linear least squares fit (pixel-by-pixel) to a subset of the data. In this process each pixel of the spectrum is treated separately, as if it represented a time series. Data taken while the light from the star was varying (declining) dramatically were excluded because such variations could mimic the pattern of variation of the geocoronal flux, and result in a contamination of the geocoronal spectrum with a small admixture of the stellar spectrum. The geocoronal spectrum derived by this scheme is shown in Figure 4. It comprises a Lyα line with a very broad and skewed profile, and a much weaker O i λ1304 line with a profile which is equally broad but nearly flat topped. Figure 4 also includes, for comparison, the inverse sensitivity function of the combination of the Blue Digicon detector and the G160L grating. The skewed profile of the geocoronal Lyα line follows very closely the steep rise of the inverse sensitivity function towards 1150 Å.
Figure 1. – The profile of the geocoronal Lyα line from the spectrum of 4C 73.18. The top panel shows the inverse sensitivity function for reference while the other two panels depict the line profile in the count rate and flux spectra. The profile in the latter spectrum is skewed as a result of multiplication with the inverse sensitivity function. The spectrum was taken in $\frac{1}{4}$-stepping mode through the 3'.66 × 3'.71 aperture (post-COSTAR) using the G130H grating.

Figure 2. – An enlarged view of the spectrum of AE Aqr around the Lyα/N v blend, taken with the G160L grating and the 4''3 aperture. The spectrum presented here is the average of many exposures taken in RAPID mode. The intrinsic emission lines from the star and the geocoronal lines are identified. The two types of lines can be distinguished from their dramatically different profiles.

Figure 3. – A comparison of the continuum light curve of the star with the light curve of the geocoronal Lyα line. The continuum light curve represents the variation of star’s continuum in the 2000 – 2200 Å bandpass, far away from the geocoronal emission lines. The geocoronal Lyα light curve represents the variation of the blue side of the line, which is not affected by intrinsic variations of the light from the star.

Figure 4. – The spectrum of the geocoronal emission (obtained using the linear decomposition scheme described in the text) compared to the shape of the inverse sensitivity function of the appropriate instrument configuration. The skewed profile of the geocoronal Lyα line follows very closely the steep rise of the inverse sensitivity function towards 1150 Å. The spectrum was obtained through the 4''3 aperture with the G160L grating in $\frac{1}{4}$-stepping mode.
Figure 5. — Model profiles of the geocoronal Lyα and O I λ1304 lines compared to the data. The profiles themselves are shown separately in the upper and middle panels, and they are superposed to the observed profiles (after a suitable scaling) in the lower panel. The spectrum was obtained through the 4′3 aperture with the G160L grating in 1/2-stepping mode.

Figure 6. — The profiles of the geocoronal emission lines obtained through the 3′66 × 3′71 aperture (post-COSTAR) using the G130H grating in 1/4-stepping mode.

3. Model Line Profiles for a Large Rectangular Aperture

A model for the profiles of the geocoronal lines can be developed by considering how the geocoronal line photons are recorded by the detector array. Since the emission is diffuse and fills the rectangular spectrograph aperture, the line profiles in the photon (raw count) spectrum should be flat topped, and smoothed by the grating’s line-spread function. The widths should correspond to the combination of the projected size of the aperture on the detector array, and the width of the line-spread function. In the calibration process the spectra are multiplied by the inverse sensitivity function in order to generate the flux scale. The inverse sensitivity function is very steep near the blue end of the spectrum, with the consequence that it makes the originally flat-topped geocoronal line profiles in the photon spectra skewed and asymmetric after flux calibration. The above model was used to simulate the profiles of the geocoronal Lyα and O I λ1304 lines. The original line profiles were assumed to be square, centered at the nominal wavelengths of the lines, with widths of 12 diodes (=24 pixels, since the spectrum is 1/2-stepped over diodes), corresponding to the projected size of the 4′3 aperture (each diode has a width of 0′36 in the pre-COSTAR configuration; Keyes et al. 1995). We note that the assumption of square line profiles is, strictly, an approximation which holds only when the projected size of the aperture is considerably larger than the size of a diode (and also a spectral resolution element). In the next section we examine the case where the aperture size is comparable to the size of a diode and this approximation is not valid. The square profiles were then convolved with a Gaussian filter with a full width at half maximum of 2.
pixels (1 diode), to simulate broadening by the line spread function, and multiplied by the inverse sensitivity function (inspired by Evans 1993). The resulting model profiles are displayed in the first two panels of Figure 5. The lowest panel of Figure 5 shows the model profiles superposed on the observed profiles derived from the data as described above. The observed profiles have been arbitrarily normalized to unit maximum. The model profiles were scaled to fit the data using a linear least squares method ($\chi^2$ minimization). The good agreement between the data and the models demonstrates both the validity of the model and the success of the linear decomposition scheme used to derive the observed geocoronal line profiles from the data. The same model is also applied to the geocoronal line profiles in the spectrum of 4C 73.18 and the results are shown in Figure 6.

4. Line Profiles for Small Circular and Rectangular Apertures

The above method for modelling the line profiles of the geocoronal lines can be extended to the smaller, circular and rectangular apertures used in most post-COSTAR science observations. The fundamental difference between the small and large apertures is that their sizes are comparable to the width of a diode (and hence also to a spectral resolution element). This means that the geocoronal line profile will be intrinsically bell-shaped because adjacent diodes intercept different amounts of light from the projected image of the aperture. Thus, the main subtlety involved in this step is the computation of the line profile from a diffuse source that fills the small circular aperture. Below we carry out this exercise using the 0.86 diameter circular aperture as an example. The same method and formulae can be applied to the pre-COSTAR 1.0 square aperture as well. The model profiles are compared to the observed geocoronal Lyα and O I λλ1302,1306 profiles from a long observation of Arp 102B whose intrinsic lines are not blended with the geocoronal lines and to the line profile from an observation of the supernova remnant N49 whose intrinsic Lyα line is very weak. Because the inverse sensitivity function does not vary dramatically over the width of the lines we expect that the line profiles should be roughly symmetric, as observed, in contrast to the profile from the 4.3 aperture.

In Figure 7a we show to scale the projection of the 0.86 circular aperture onto the diode array (in the post-COSTAR configuration each diode has a width of 0.31 and a height of 1.29; Koratkar et al. 1995). It is obvious that for a diffuse source filling the aperture, different diodes receive different amounts of light according to their location relative to the center of the image. Moreover, as the image is effectively moved relative to the diode array in the sub-stepping procedure the amount of light intercepted by a given diode also changes accordingly. This principle, which determines the intrinsic profile of the geocoronal lines, is illustrated in Figure 7b where the relative positions of

**Figure 7.** (a) The image of the 0.86 circular aperture projected onto the diode array (to scale). (b) A graphical illustration of the amount of light of the image of the aperture intercepted by a diode at different offsets from the center of the image. The offsets shown correspond to the actual offsets of the detector pixels.
the aperture image and a single diode are plotted for different separations between the centers of the image and the diode. To construct the profile of the resulting geocoronal line we calculate the amount of light intercepted by a diode as a function of the separation between its center and the center of the aperture image. For a diode of full width $w$ centered a distance $x$ from the center of the image whose radius is $r$ (see Figures 7a, b) the fraction of the image flux it intercepts is

$$\frac{F(x, w)}{F_{\text{total}}} = \frac{1}{\pi} \left[ \Phi \left( \frac{z}{r} \right) - \Phi \left( \frac{x - w}{2r} \right) \right] \quad \text{if } x < r + \frac{w}{2}$$

$$= 0 \quad \text{otherwise}$$

(2)

where $F_{\text{total}}$ is the total flux in the image, $z = \min \{ r, (x + \frac{1}{2}w) \}$, and the function $\Phi(\xi)$ is defined as

$$\Phi(\xi) = \sin^{-1} \xi + \xi \sqrt{1 - \xi^2}$$

(3)

with $\xi \leq 1$ by definition. As a consistency check for this formula we note that $F(0, 2r) = F_{\text{total}}$, i.e., if the diode is centered on the center of the image and has a full width equal to the image diameter, it intercepts all of its flux. As in §2, the intrinsic profiles of the geocoronal lines are computed using the above prescription, convolved with the grating’s line spread function (assumed to be a Gaussian of full width at half maximum of 4 pixels = 1 diode). The resulting model profiles are shown in the upper panels in Figure 8, and they are compared to the observed profiles in the lower panels of the same figure.
It is straightforward to construct an analogous model for the pre-COSTAR 1°0 square aperture, or the post-COSTAR 0°86 square aperture, which was used for a significant fraction of the post-COSTAR FOS/BLUE G160L science observations. For a diode of full width \( w \) centered a distance \( x \) from the center of the image of a square aperture whose width is \( a \) the fraction of the image flux it intercepts is

\[
\frac{F(x, w)}{F_{\text{total}}} = \frac{1}{a} \left[ \min \left\{ \frac{a}{2}, \left( \frac{x + \frac{w}{2}}{2} \right) \right\} - \left( \frac{x - \frac{w}{2}}{2} \right) \right] \quad \text{if } x < r + \frac{w}{2} \\
= 0 \quad \text{otherwise}
\]  

(4)

where the symbols have the same meaning as in equation (2). This model is compared to the corresponding line profiles in Figure 9. It is noteworthy that the line profiles from the circular and square apertures are appreciably different; the latter aperture produces a profile with a rather round top and slightly larger width.

5. The Moral of the Story

The principles described in §4 can be used to simulate the geocoronal line profiles for almost any aperture. The only subtle issue to be kept in mind is that the intrinsic profile of the line depends critically on the amount of light intercepted by each diode when the image of the aperture is projected on the diode array. It is unfortunate that the width of the geocoronal lines through the 0°86 circular and square apertures is likely to be comparable to the intrinsic width of emission lines from the target of the observation, making it very difficult to deblend the two (the full width at half maximum of the geocoronal Lyα line of Figure 8 is 6.7 Å, or 1650 km s\(^{-1}\)). In the case of the 4°3 aperature, however, the geocoronal lines are so broad that they form a pedestal under the intrinsic emission lines from the target of the observation. Under these circumstances, knowledge of the profiles of the geocoronal lines allows one to subtract them successfully (as demonstrated by Eracleous & Horne 1996).

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REFERENCES