Calibrated H I Lyman α Observations with TRACE

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Abstract. Since shortly after launch in April 1998, the *Transition Region and Coronal Explorer* (TRACE) observatory has amassed a collection of H I Ly α (1216 Å) observations of the sun that have been not only of high spatial and temporal resolution, but also spanning a duration in time never before achieved. The Ly α images produced by TRACE are, however, composed of not only the desired line emission, but also local ultraviolet continuum and longer wavelength contamination. This contamination has frustrated attempts to interpret TRACE observations in H I Ly α.

The Very Advanced Ultraviolet Telescope (VAULT) sounding rocket payload was launched from White Sands Missile range May 7, 1999 20:00 UT. The VAULT telescope for this flight was a dedicated H I Ly α imaging spectroheliograph. We use TRACE observations in the 1216 Å and 1600 Å channels along with observations from the VAULT flight to develop a method for removing UV continuum and longer wavelength contamination from TRACE Ly α images.

1. Introduction

The *Transition Region and Coronal Explorer* (TRACE, Handy et al., 1999) observatory is unique in that it is able to do extended, high-cadence imaging observations of the solar transition region; a previous paper has discussed the methodology of analyzing observations of the C IV 1548 and 1550 Å resonance line pair (Handy et al., 1998). This study described how images taken through the C IV filter set were substantially contaminated by neighboring UV continuum and, to a lesser extent, long-wavelength (e.g. visible) light and how it was possible to remove much of this non-C IV contamination using a combination of images through different filters. Much purer images of the transition region are then realized.

It was known prior to launch that the H I Ly α (1216 Å) channel would be similarly affected by non-Ly α emission. It is subject to a double peak in spectral response with one peak located at $\sim$1216 Å and a second peak situated at approximately 1550 Å(see Figure 1). This

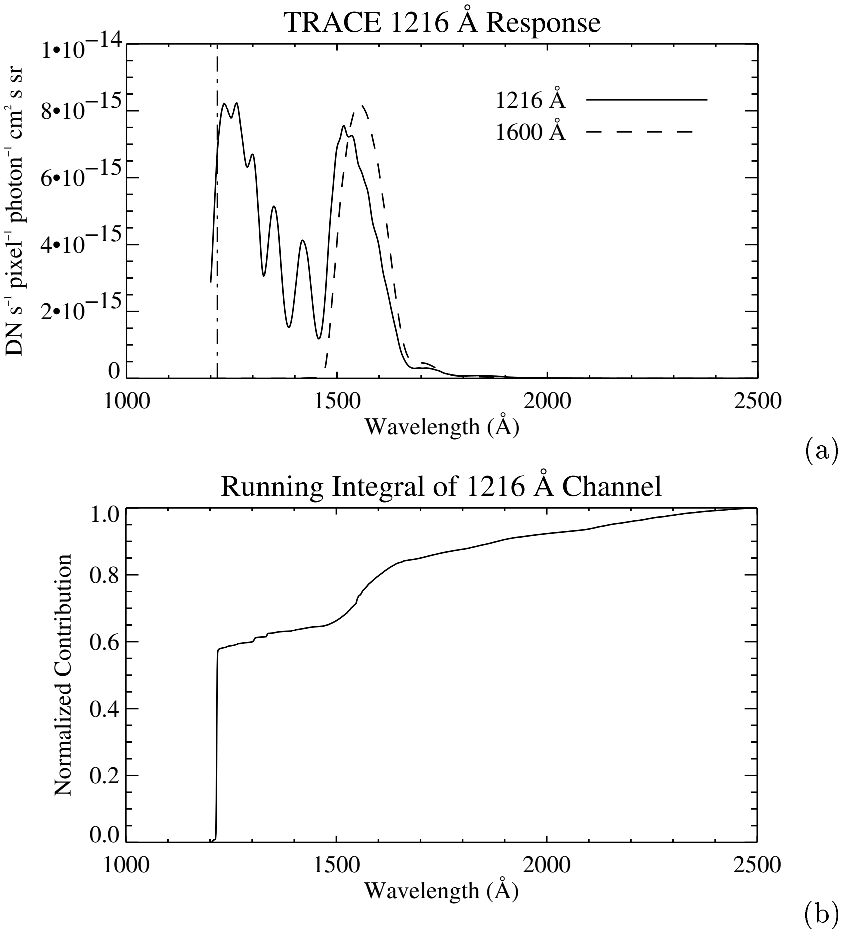


Figure 1. Response of the TRACE 1216 Å and 1600 Å channels. In (a) the double peak in the response of the 1216 Å channel is clearly visible. The 1600 Å filter curve has been normalized to the response of the 1216 Å filter for comparison of the respective bandpasses, and the location of the Ly α emission line center is shown. A running integral of the spectral contribution to the image is shown in (b), to emphasize the spectral contribution by wavelength.

unusual spectral response results from the convolution of a narrowband UV coating on the primary mirror at 1500 Å and a filter near the focal plane centered at 1216 Å. Figure 1(b) shows a running integral of the spectral response, e.g.

$$C(\lambda) = \frac{\int_{1200}^{\lambda} R(\lambda')F(\lambda')d\lambda'}{\int_{1200}^{2500} R(\lambda')F(\lambda')d\lambda'}, \tag{1}$$

where $R(\lambda)$ is the response function of the Ly α channel, $F(\lambda)$ is the solar flux, and $C(\lambda)$ represents the spectral contribution function to a given pixel in a TRACE Ly α image. Figure 1(b) illustrates the spectral contribution to the Ly α image. From the figure it is evident that $\approx$60% of the signal in the Ly α image is from the Ly α 1216 Å emission line while the balance of the signal is from UV emission near 1550 Å and longer wavelengths. Simple calculations prior to launch suggested that the C IV emission near 1550 Å could be dealt with since the Ly α emission line is typically a much brighter line. Prelaunch models indicated that the 1216 Å channel would contain $\sim$50% Ly α emission and the remainder would be UV continuum and 1550 Å emission. The calibration information used in this paper is from the pre-launch calibration of the individual elements in the optical path. The data is available in the TRACE instrument paper (Handy et al., 1999) and is also available in the TRACE SolarSoft package (SSW, Freeland and Handy, 1998).

It was not entirely clear prior to launch if this contamination could be corrected for. The spectral data used for the C IV analysis were based largely on data from the High Resolution Telescope and Spectrograph (HRTS, Dere et al., 1984). While this data proved to be an excellent source for studying C IV emission over a variety of solar conditions, the sensitivity of the instrument at 1216 Å was too low for the desired Ly α analysis (c.f. Brekke, 1993 for a graph of the HRTS spectral sensitivity).

Recent Ly α observations by other instruments have inspired a return to this problem. A simple model of the TRACE Ly α correction was generated using a large sample of data from the *Solar Stellar Irradiance Comparison Experiment* (SOLSTICE, Rottman et al., 1993) and further refined with observations from the *Very Advanced Ultraviolet Telescope* (VAULT, Korendyke et al., 1996) sounding rocket flight of May 7, 1998. We also study study limb observations to further characterize the UV continuum leakage in the Ly α channel.

2. Observations

Several separate sets of observations were used in the analysis that follows. They are detailed in the following sections.

2.1. SOLSTICE DAILY IRRADIANCE SPECTRA

The first step towards an approximate calibration of the TRACE Ly α channel was to aquire a large statistical sample of solar spectra showing variation in the Ly α emission line and also in the intensity level of the neighboring UV continuum. The largest collection of applicable observations has been by the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE, Rottman et al., 1993). A primary science product of SOLSTICE is a daily mean solar UV spectrum, covering approximately 1150–4250 Å, giving the Solar irradiance in units of W m^{-3} (1 W m^{-3} = 10^{-7} erg s^{-1} cm^{-2} Å^{-1}) with a resolution of 1 nm. This full-disk average is suitable for this model for several reasons: first, it is extremely beneficial to have both the response of the 1216 Å emission line and the long-wavelength UV continuum in the same dataset. Secondly, the SOLSTICE data archive (collected over a period of about 5 years) is the most comprehensive set of spectral observations available. Finally, this method of extracting the Ly α emission from the UV continuum background is only an approximation and the accuracy of the final result will not be severely impacted by the average nature of the input spectra.

For our analysis, a data sample of one spectrum per month for approximately five years was selected from the SOLSTICE level 3BS (version 9) data archive. This data covers the time period from 3 October 1991 through 31 December 1996.

2.2. VAULT SOUNDING ROCKET FLIGHT

The VAULT sounding rocket payload is composed of a 30 cm aperture Cassegrain telescope, a zero dispersion H I Ly α 1216 Å spectroheliograph and a 3072×2048 CCD. The Ly α filter has a bandpass of 150 Å and the spatial resolution of the telescope is $\approx$0.25 arc sec (Korendyke et al., 1996).

VAULT was launched from White Sands Missile Range on May 7, 1999 at 20:01:00 UT. The telescope doors were opened at 20:02:40 UT and observations stopped at 20:07:12 UT. During the flight VAULT made a continuous set of observations in H I Ly α 1216 Å. TRACE meanwhile made a full set of synoptic observations at the selected VAULT field of view before and after the VAULT flight, and ran a high-cadence Fe IX (171 Å) movie during the flight for the purpose of comparing transition region phenomena to high-cadence coronal observations. For this work, we compare the first available Ly α image from the VAULT flight, taken at 20:02:40 UT, to a TRACE 1216 Å image taken just prior to the flight at 19:58:38 UT.

2.3. TRACE ON-DISK AND OVER-THE-LIMB CALIBRATIONS

This analysis uses three Ly α observations made with the TRACE instrument. The on-disk observation (made in concert with the VAULT flight, section 2.2) demonstrates the level of UV continuum present in the Ly α images. We also study two limb observations made with TRACE:

1. An observation of a prominence over the northwest limb taken at 1 October 1998 at 10:06 UT. This observation collected images in the 1216, 1216L, 1600, and 1700 channels. We use these data to appraise the contamination level in Ly α limb observations.
2. We employ data from a synoptic campaign run in 1999 to observe a double limb present on the northeast and southwest limbs. This faint double-limb effect is due to a wedge of a few arc seconds in the MgF_2 entrance filter of the UV channel.

3. Analysis

The analysis of TRACE Ly α observations was effectively composed of two separate efforts. The first effort, based entirely on pre-launch calibration data (Handy et al., 1999) and irradiance data from the SOLSTICE mission, served to create a strawman method of reducing a dataset composed of a pair of 1216 Å and 1600 Å images to a truer representation of the solar Ly α emission. These results were then applied to data collected during the time of the VAULT flight for a visual inspection of the respective Ly α images from the two telescopes. Analysis of observations of the solar limb were used to further describe the UV continuum leak in the Ly α channel.

3.1. SOLSTICE CALIBRATION

The method of calculating the UV contamination in the 1216 Å channel is very analogous to that employed for the TRACE C IV channel (c.f. Handy et al., 1998). Using the SOLSTICE database of solar spectra spanning a wide range of solar activity, calculate the predicted count rates through the 1216 Å channel and the 1600 Å channel, and compare these measured intensities to that of the Ly α emission line through the 1216 Å channel, e.g. beginning with the following images:

$$\begin{aligned} I_{1216} &= 1216 \text{ Å image} \\ I_{1600} &= 1600 \text{ Å image} \end{aligned} \tag{2}$$

The count rates represented by I_{1216} and I_{1600} are calculated by folding the SOLSTICE spectra against the TRACE 1216 Å and 1600 Å channel response functions. Then, by assuming the solar spectrum is composed of (a) Ly α 1216 Å emission and (b) longer-wavelength UV continuum, one may simplify the problem:

$$I_{\mathrm{Ly}\,\alpha} = A \times I_{1216} + B \times I_{1600}, \tag{3}$$

where A and B are constants to be determined, and $I_{\mathrm{Ly}\,\alpha}$ represents the actual number of counts in the Ly α channel that are due to Ly α emission. One dataset is composed of these numbers calculated from one spectral dataset from SOLSTICE. A least-squares regression was then applied to the resulting matrix of data to calculate best fit solutions for A and B. The values calculated from this least-squares fit are $A = 0.97$ and $B = -0.14$.

This exercise serves two purposes. First, it serves as a sanity check for the model: the coefficient for the 1216 Å image should be very near unity, and the coefficient for the 1600 Å image should be expected to be small and negative. The former indicates very little Ly α emission appears in the 1600 Å images. The second purpose is to serve as an initial guess for fine-tuning with the VAULT observations in the following section.

3.2. Comparison to VAULT observations

It is possible to use the coefficients modeled in section 3.1 to create corrected TRACE Ly α images of good quality. However, it is possible to further refine these coefficients further by comparison with images from the VAULT flight.

To improve the correction method further, the VAULT images are rebinned and coaligned to the corresponding TRACE images of the same time period. Then, the intensities of the corrected TRACE Ly α image are compared to the corresponding intensities in the VAULT Ly α image. Assuming the VAULT Ly α images to be effectively free of non-Ly α emission, we can use the *Spearman Rank-Order Correlation Coefficient* (Press et al., 1992) to optimize the correction algorithm further. This was accomplished by holding the coefficient A constant and varying B to locate the point of highest correlation between the VAULT and TRACE Ly α images. The best-fit coefficients are:

$$\begin{aligned} A &= 0.97 \\ B &= -0.105 \end{aligned} \tag{4}$$

The next logical step is a visual comparison, shown in figure 2. The level of UV continuum present in the TRACE 1216 Åimages is quiet evident in this comparison. The correction algorithm removes much of the high contrast chromospheric network granulation, resulting in an image much closer in appearance to the VAULT image. The VAULT

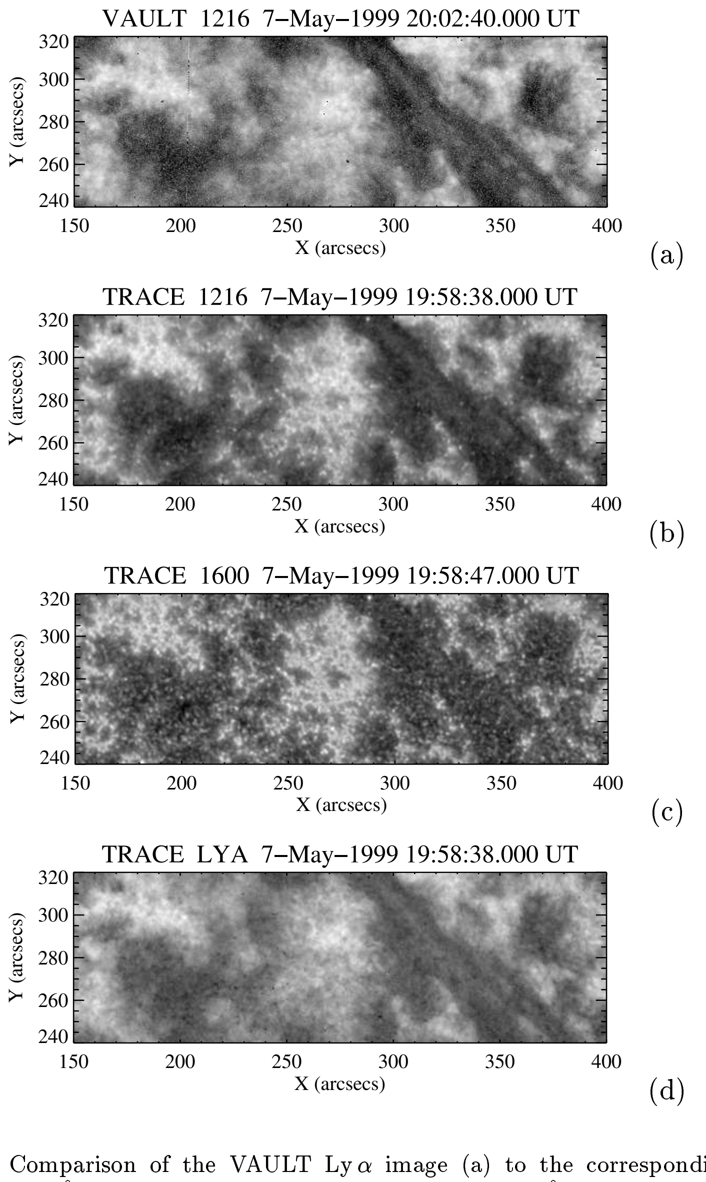
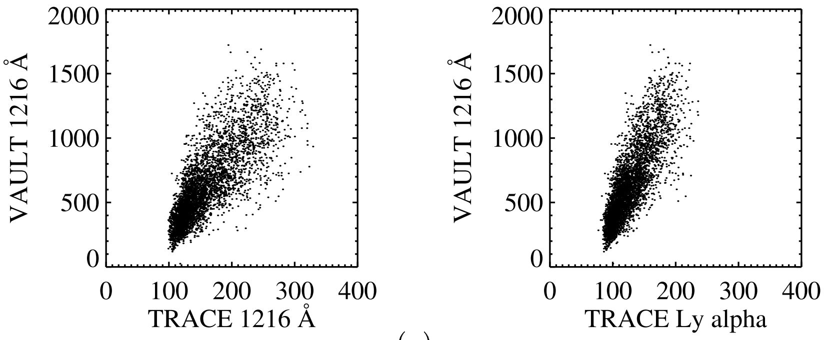


Figure 2. Comparison of the VAULT Ly α image (a) to the corresponding raw TRACE 1216 Å image (b), corresponding TRACE 1600 Å image (c), and the processed TRACE Ly α image (d).

data is uncalibrated so a detailed comparison of observed intensities is not possible. However, it is reasonable to compare relative intensities between the VAULT and TRACE images, shown in figure 3).



(a) (b)

Figure 3. Comparison of the TRACE raw and corrected images versus data from the VAULT flight. Plot (a) is a comparison of the raw TRACE 1216 Å channel intensity in figure 2 to the corresponding VAULT Ly α image. (b) is a comparison after the TRACE images were corrected for Ly α contamination using the coefficients from section 3.2.

The improvement in the TRACE Ly α image is demonstrated by the Spearman coefficients: prior to correction, the correlation between the TRACE 1216 Å image and the VAULT image is given by the Spearman rank correlation coefficient $r_s = 0.809$. After correction, the correlation improves slightly to $r_s = 0.825$. The correction effect is a subtle one but it is apparent in the processed images. Plot (a) in figure 3 compares the relative pixel-by-pixel intensities of the VAULT Ly α image to those of the unprocessed TRACE 1216 Å image in a field of view slightly larger than that of figure 2. Plot (b) compares the VAULT image to the corrected TRACE Ly α image.

3.3. TRACE limb observations

To futher characterize the continuum leakage in the 1216 Å channel, it is useful to study limb observations through the different available filter combinations. Pre-launch calibrations (Handy et al., 1999) predict the level of contamination to be expected in this channel, but it is useful to see qualitatively the level of non-Ly α emission present in the images. The first image in figure 4 is an uncorrected 1216 Å image of the prominence. The second image is the same field of view but with the 1600 Å filter also in the light path of the telescope. This filter combination is referred to as "1216L," and the 1600 Å filter removes all Ly α emission from the image because it cuts off sharply at approximately 1450 Å.

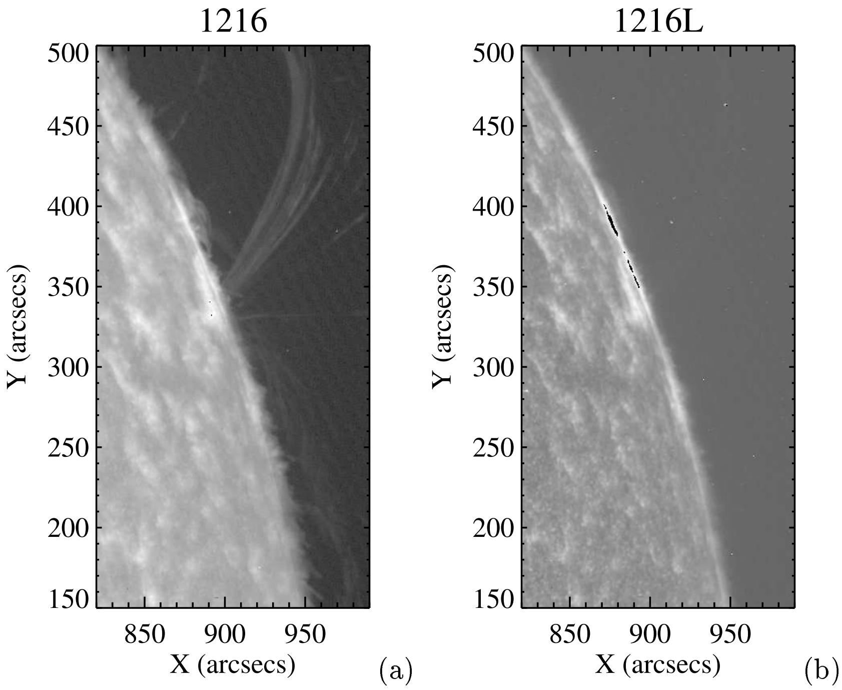


Figure 4. A limb observation demonstrating the UV continuum leak in the 1216 Å channel. Image (a) is the NW limb observed through the TRACE 1216 Å channel. This observation was made at 1 October 1998 10:06:19 UT. Image (b) is the same FOV at 10:06:25 UT through the 1216L channel (described in the text). UV continuum emission in the Ly α channel is evident on disk, but this observation shows a very low level of contamination in the prominence.

An additional complication that becomes apparent in studying limb observations is a manifestation of a slight "wedge" in the MgF_2 entrance filter. The surfaces of the MgF_2 entrance filter were specified to be parallel to < 5 arc seconds, and the flight filter was measured to be $\approx$2–3 arc seconds. Since the indices of refraction for MgF_2 vary over the range of 1200–1600 Å, this wedge is manifested as a shift of 1–2 arc seconds in the UV continuum image relative to the Ly α image (Figure 5). This effect is a very small one, and is nearly imperceptible on the NE limb.

The correction mechanism described in this paper is able to remove part of the ghosted limb, but it is evident that corrected limb images are still not right. What is left is evidently some form of limb brightening that isn't corrected by this method.

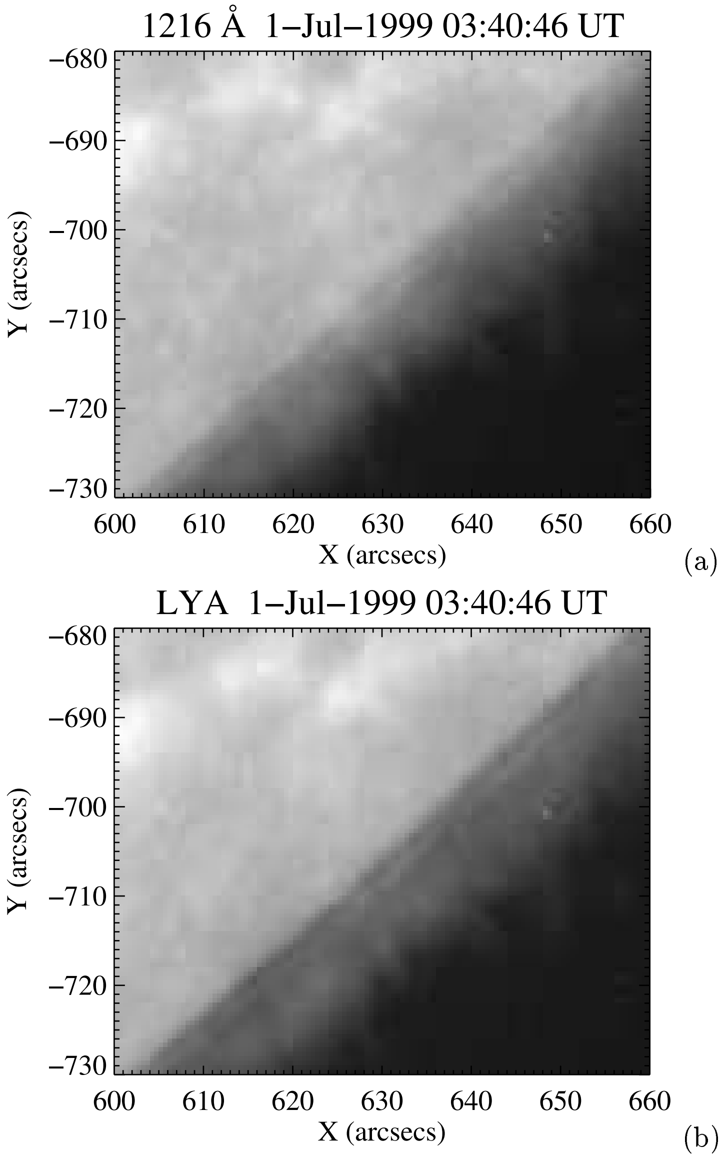


Figure 5. A manifestation of the wedge in the UV entrance filter. In (a) a ghost of the UV continuum (present in the 1600 image) is evident as a bright band about 2 arc seconds above the limb. Correlating the 1216 and 1600 Å images to one another places the 1600 Å limb squarely on this ghost limb. Image (b) is the result of applying the correction algorithm to the TRACE image used in (a). The ghost is still evident after correction.

4. Discussion

The TRACE observatory has made possible an unprecedented opportunity to study the solar atmosphere using the H I Ly α 1216 Å emission line. The method presented in this paper, removing the UV continuum from the 1216 Å images by subtracting a small part of the 1600 Å signal, should improve studies of many legacy TRACE observations that collected both 1216 and 1600 Å images. We believe it will also encourage future observers to consider including Ly α studies in their observing programs.

It is important to note that the method presented here is by no means exact. Researchers seeking high precision photometry measurements of Ly α from TRACE should pay heed to the level of accuracy that is reasonable. This method assumes a reasonably predictable UV continuum background in lieu of actual measurements of said background. That aside, we believe these measurements apply anywhere on the solar disk, in quiet sun regions or bright active regions. The method does not work well above the solar limb, and the level of complexity there currently discourages a very high level of accuracy.

Future efforts will involve cross-calibration with the SUMER instrument on SOHO (Wilhelm et al., 1995). On June 8, 1999 SUMER and TRACE performed a joint intercalibration JOP that co-observed Ly α emission in the quiet network near disk center. Analysis of this observation is in process and the results will be used to further refine the correction. An IDL routine, `lya_subtract.pro`, has been added to the *Solarsoft* tree and will be available with the SSW/TRACE software distribution.

5. Acknowledgments

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