15.11: The *GALEX* Comets

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October 2009 DPS Meeting

Abstract

The Galaxy Evolution Explorer (*GALEX*) has observed 6 comets since 2005 (C/2004 Q2 (Machholz), 9P/Tempel 1, 73P/Schwassmann-Wachmann 3 Fragments B and C, 8P/Tuttle and C/2007 N3 (Lulin). *GALEX* is a NASA Small Explorer (SMEX) mission designed to map the history of star formation in the Universe. It is also well suited to cometary coma studies because of its high sensitivity and large field of view (1.2°). OH and CS in the NUV (1750 – 3100 Å) are clearly detected in all of the comet data. The FUV (1340 – 1790 Å) channel recorded data during three of the comet observations and detects the bright C I 1561 and 1657 Å multiplets. We also see evidence of S I 1475 Å in the FUV. **NEW: we clearly detect CO$^+$ emission in the NUV and CO Fourth positive emission in the FUV.**

The *GALEX* data were recorded with photon counting detectors, so it has been possible to reconstruct direct-mode and objective grism images in the reference frame of the comet. We have also created software which maps coma models onto the *GALEX* grism images for comparison to the data.

We will present the data cleaned with automated catalog-based methods and a preliminary hand-fit to the data using simple Haser-based models. A more thorough hand-cleaning of the data from the contaminating effects of background sources is the last major reduction task to be done. This cleaning will allow quantitative parameter optimization of the models being fitted to the data.

Even at this stage, the residuals between the data and models show interesting radial and azimuthal structure at large cometocentric distances (e.g., 50,000 – 250,000 km) in at least two comets (Machholz and Lulin). Due to the general lack of wide-field UV space-based imaging capabilities longward of H-Lyman alpha, *GALEX* provides some of the only data in this extended region of the UV cometary coma.

Keywords: Comets, coma studies, OH, CS, C I, S I
Executive Summary

The Galaxy Evolution Explorer (GALEX) is a NASA Small Explorer mission designed to map the history of star formation in the Universe using two modes: two-band photometry (FUV 1350–1750 Å and NUV 1750–2800 Å) and objective grism spectroscopy (10–20 Å resolution) (Martin et al., 2005). The 1.2 degree FOV diameter and high sensitivity to extended sources ideally suits GALEX to cometary coma studies as well.

GALEX has observed the 6 comets listed in Table. NUV grism observations were obtained for all of the comets and FUV grism observations for Machholz, Tuttle and Lulin. Figure 1 shows the basic data reduction scheme and what grism observations of comets look like.

In order to make the best use of the simultaneous spatial and spectral information in the grism images and assess the quality of the data, we have generated simple axisymmetric models and subtracted them from the data. In the attached pages, we present the data and residuals.

We find that in general, the residuals in the NUV (dominated by OH 3080 and CS 2576 Å) are reasonable beyond 1–5×10^4 km in directions not obviously dominated by dust or ion emission. Notable exceptions to this are Tuttle on 2008-Jan-01 (possibly the Greenstein effect) and Lulin on 2009-Feb-20 (possibly a viewing geometry effect). This suggests that the simple model based on standard H_2O and CS_2 photochemical parameters (see Model page) describes the NUV data reasonably well.

In the FUV, models generated using standard parameters do not fit the data well. The primary problem seems to be with the CO and/or C I scale lengths. Rather than adjust these parameters in this work, we have concentrated on varying production rates to explore all of the detectable emission in the FUV bandpass. By using the wavelength offset of the grism we are able to inspect the residuals and find evidence for either unexpectedly active S I 1425 and 1475 Å emission (unlikely) or CO Fourth Positive emission.

The simultaneous detection of CO Fourth Positive and C I emission gives us the potential to address some some long unanswered questions. Assuming CO is the dominant source of C I, we will be able to measure the lifetime of C I against solar photo and solar wind ionization processes given an assumed outflow velocity. With information about the C I lifetime we will be able to work backwards with our CO distribution to constrain the the source(s) of CO.
Model

We use the 2-component Haser (1957) model to create radial density distributions for the species listed in Table 2.

The parent outflow velocities are assumed to be the same and given by the H$_2$O outflow velocity derived by Budzien et al. (1994). In the case of CS, since CS$_2$ has such a short lifetime, we assumed it would be entrained in the bulk outflow as well. For the parent-daughter pairs indicated with a Y in the CV column of the Table, we use the prescription in Combi et al. (2004) to convert the velocities into Haser-equivalent velocities adjusted to emulate the vectorial model (Festou, 1981).

Using the velocities and lifetimes in the Table for CO and C I and the Combi et al. prescription, we did not achieve good fits to the C I distribution. Instead, we used the original bulk outflow velocity for CO and added that in quadrature with the C I ejection velocity for the daughter velocity. This only resulted in a good fit for the Lulin 2009-Mar-06 data. As noted in the presentation of the Machholz and Lulin 1009-Feb-20 data, the comets may have exhibiting outbursts.

The particle density distributions calculated above were integrated numerically along the line of site to create column density distributions. For the wavelengths of the molecular bands or atomic multiplets, a heliocentric velocity dependent $g$-factor was calculated. For OH we used Schleicher & A’Hearn (1988); C I, McPhate et al. (1999) and for S I, a calculation by Paul Feldman using high resolution solar spectra from SMM normalized to absolute fluxes from SOLSTICE and scaled as suggested by Federman & Cardelli (1995).

The 1D density distributions were scaled by the appropriate $g$-factors and transformed into 2D axisymmetric distributions as figures of rotation. For each observation, the GALEX pipeline provides a cross dispersion response based on the average of several bright stars in the FOV. We creating a figure of rotation out of this profile and to estimate a 2D PSF. This is convolved into our model coma image. The resulting image is scaled by the GALEX effective area and placed according to the GALEX grism dispersion relation.

In the case of dust in the NUV, we use a simple axisymmetric $1/\rho$ column density distribution convolved by the GALEX PSF and the solar spectrum.
Table 1: Wavelengths of features (Å)

<table>
<thead>
<tr>
<th></th>
<th>OH</th>
<th>CS</th>
<th>CI</th>
<th>SI</th>
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<tr>
<td></td>
<td>3086</td>
<td>2576</td>
<td>1657</td>
<td>1813</td>
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<td></td>
<td>2826</td>
<td>2663</td>
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<td></td>
<td>2620</td>
<td>2507</td>
<td>1425</td>
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1 The $g$-factor for this band is very small. The maximum value is used instead of calculating a heliocentric velocity dependence.

Table 2: Model Parameters

<table>
<thead>
<tr>
<th>Species</th>
<th>Lifetime¹</th>
<th>Reference</th>
<th>Velocity²</th>
<th>CV³</th>
<th>Reference</th>
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<tr>
<td>H$_2$O</td>
<td>83,000</td>
<td>Huebner⁴</td>
<td>0.85</td>
<td>r$^{-0.5}$</td>
<td>Y Budzien et al. (1994)</td>
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<tr>
<td>OH</td>
<td>133,000</td>
<td>Huebner⁴</td>
<td>0.98</td>
<td>Y</td>
<td>Crovisier (1989)</td>
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<tr>
<td>CS$_2$</td>
<td>1,000</td>
<td>Feldman⁵</td>
<td>H$_2$O</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>155,000</td>
<td>Smith⁶</td>
<td>H$_2$O</td>
<td>N</td>
<td></td>
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<tr>
<td>CO</td>
<td>500,000</td>
<td>Huebner⁴</td>
<td>H$_2$O</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>C I</td>
<td>1.6×10⁶</td>
<td>Woods⁷</td>
<td>4</td>
<td>N</td>
<td>Feldman⁹</td>
</tr>
<tr>
<td>H$_2$S</td>
<td>4,150</td>
<td>Eberhardt⁸</td>
<td>H$_2$O</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>S I</td>
<td>910,000</td>
<td>Huebner⁴</td>
<td>0.63</td>
<td>Y</td>
<td>Huebner et al. (1992)</td>
</tr>
</tbody>
</table>

¹ seconds at 1 AU, solar quiet conditions assumed for all comets
² km s$^{-1}$; Molecular dissociation ejection velocities quoted for daughters
³ velocities adjusted by prescription in Combi et al. (2004) (see text)
⁴ Huebner et al. (1992)
⁵ Feldman et al. (1999)
⁶ Smith et al. (1980)
⁷ Woods et al. (2000)
⁸ Eberhardt et al. (1994)
⁹ Feldman private communication, 2005
Table 3: Summary of *GALEX* observations and production rates used in the models

<table>
<thead>
<tr>
<th>Comet</th>
<th>UT Date</th>
<th>$r$</th>
<th>$\Delta r$</th>
<th>$\dot{r}$</th>
<th>Q(OH) $10^{28}$ s$^{-1}$</th>
<th>Q(CS) $10^{25}$ s$^{-1}$</th>
<th>$A f \rho$ cm</th>
<th>Q(C I)$^1$ $10^{28}$ s$^{-1}$</th>
<th>Q(S I)$^1$ $10^{26}$ s$^{-1}$</th>
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</thead>
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<tr>
<td>Machholz</td>
<td>2005-Mar-01</td>
<td>1.32</td>
<td>0.78</td>
<td>10.9</td>
<td>12</td>
<td>6</td>
<td>1600</td>
<td>7</td>
<td>1</td>
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<tr>
<td>9P/Tempel 1</td>
<td>2005-Jul-02</td>
<td>1.51</td>
<td>0.89</td>
<td>-0.3</td>
<td>0.7$^2$</td>
<td>0.1$^2$</td>
<td>120</td>
<td>60</td>
<td>120</td>
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<tr>
<td></td>
<td>2005-Jul-04</td>
<td>1.51</td>
<td>0.90</td>
<td>-0.1</td>
<td>0.7</td>
<td>0.1</td>
<td>120</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2005-Jul-05</td>
<td>1.51</td>
<td>0.90</td>
<td>0.0</td>
<td>1.1</td>
<td>0.16</td>
<td>160</td>
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<tr>
<td>73P/SW3 B</td>
<td>2006-May-02</td>
<td>1.08</td>
<td>0.12</td>
<td>-12.0</td>
<td>0.7</td>
<td>1.6</td>
<td>60</td>
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<tr>
<td></td>
<td>2006-May-02</td>
<td>1.08</td>
<td>0.12</td>
<td>-12.0</td>
<td>0.9</td>
<td>1.8</td>
<td>80</td>
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<tr>
<td>73P/SW3 C</td>
<td>2006-Apr-23</td>
<td>1.13</td>
<td>0.18</td>
<td>-13.4</td>
<td>0.9</td>
<td>1.2</td>
<td>100</td>
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<td></td>
<td>2006-Apr-28</td>
<td>1.10</td>
<td>0.14</td>
<td>-12.5</td>
<td>0.9</td>
<td>1.2</td>
<td>100</td>
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<tr>
<td>8P/Tuttle</td>
<td>2007-Dec-07</td>
<td>1.28</td>
<td>0.54</td>
<td>-14.8</td>
<td>1.4</td>
<td>0.7</td>
<td>75</td>
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<td></td>
<td>2007-Dec-08</td>
<td>1.27</td>
<td>0.51</td>
<td>-14.7</td>
<td>1.5</td>
<td>0.7</td>
<td>75</td>
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<td></td>
<td>2007-Dec-10</td>
<td>1.25</td>
<td>0.48</td>
<td>-14.3</td>
<td>1.7</td>
<td>0.9</td>
<td>85</td>
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<td>2007-Dec-11</td>
<td>1.24</td>
<td>0.46</td>
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<td>0.9</td>
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<td></td>
<td>2007-Dec-26</td>
<td>1.13</td>
<td>0.27</td>
<td>-10.8</td>
<td>2.9</td>
<td>1.0</td>
<td>85</td>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2008-Jan-01</td>
<td>1.10</td>
<td>0.25</td>
<td>-9.1</td>
<td>2.5</td>
<td>1.0</td>
<td>85</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Lulin</td>
<td>2009-Feb-20</td>
<td>1.37</td>
<td>0.43</td>
<td>12.1</td>
<td>8</td>
<td>3</td>
<td>700</td>
<td>5</td>
<td>1.5</td>
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<tr>
<td></td>
<td>2009-Mar-06</td>
<td>1.48</td>
<td>0.58</td>
<td>14.6</td>
<td>6.8</td>
<td>1.9</td>
<td>850</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

$^1$ The FUV model is currently still under development: these production rates are not likely to be meaningful

$^2$ McCandliss *et al.*, 2009 (in preparation) quote Q(OH) = $0.54 \times 10^{28}$ and Q(CS) = $0.067 \times 10^{25}$ s$^{-1}$
Figure 1: Counterclockwise from top right shows the progression of our data reduction scheme. GALEX pipeline products are cast in the reference frame of the stars. Using a JPL HORIZONS comet ephemeris with GALEX as the observatory, we create images in the comet frame of reference (top right). Bottom right: we effectively erase stars when we mask while accumulating counts and exposure time. Hand masking is obviously needed for some sources. Bottom left shows a linear brightness scale zoom in of the comet with the spectral features indicated. Each feature is imaged at its corresponding wavelength offset determined by the GALEX dispersion relation.
Figure 2: GALEX NUV grism observations of comet Machholz recorded 2005-Mar-01 (left) and after subtraction of our simple axisymmetric model of OH and CS emission described in the text (right). The production rates were adjusted to achieve zero residuals at large cometocentric distances. Considerable structure in the residuals is seen inside $1 \times 10^5$ km. There appears to be a dust extension, but it seems to be flowing from the position of the OH 3080 Å band. If this were spectroscopically a dust feature, it would emanate from the point between the OH and CS features (see SW3 C). This may be OH tracing H$_2$O evaporating from grains. Away from the tails, we achieve reasonably good residuals beyond $5 \times 10^4$ km. Compare to Lulin 2009-Mar-06.
Figure 3: *GALEX* FUV grism observation of comet Machholz recorded 2005-Mar-01 (left) and after subtraction of our simple axisymmetric model of C I and S I emission (right). The C I production rate was adjusted until the residual at large cometocentric distances just started to go negative (purple color). The S I production rate was lowered to the point where the 1814 Å feature stopped poking a “hole” in the residual. The extent of the residual emission is similar that that seen in the NUV but less asymmetric. The extension seen to the right is at the position of the grism 3rd order response for S I and the CO Fourth Positive features at 1400–1500 Å.
Tempel NUV Pre-Impact, During Impact

Figure 4: GALEX NUV grism observations of comet Tempel 1 on 2005-Jul-02 (left–pre Deep Impact) and 2005-Jul-04 (right–during Deep Impact). Stellar contamination will be removed in a subsequent reduction iteration.
Figure 5: GALEX NUV grism observations of comet Tempel 1 on 2005-Jul-02 (left–pre Deep Impact) and 2005-Jul-04 (right–during Deep Impact) after subtraction of the 2-D model of coma emission from OH and CS described in the text. The pre-impact image shows a very clean residual. Using the production rates of McCandliss et al., 2009 (in preparation), the residual image looks nearly identical (see Fig. 6). This image may be affected by the natural outburst that occurred contemporaneously (Feaga et al., 2008) (slight blue haze out to $0.5 \times 10^5$ km). Observations recorded over the course of several hours around Deep Impact are averaged to form the “during impact” image. This residual emission is slightly more extended than that expected from a point source.
Figure 6: Comparisons of residuals between production rates for the Tempel 1 pre-Deep Impact observations derived in this work and McCandliss et al., 2009 (in preparation) using the same radial profiles. Only slight differences are be seen (note scale difference on spectral cuts). In general we note that the model profiles used here are not the right shape, resulting in over-subtraction at large distances and under-subtraction at small distances.
Figure 7: GALEX NUV grism observations of comet Tempel 1 on 2005-Jul-05 (left) and after model subtraction (right). The model over-subtracts near the ion lines.
Figure 8: Near contemporaneous GALEX NUV grism observations of comet SW3, fragment B recorded on 2006-May-02.
Schwassmann-Wachmann 3 B NUV Residuals: Ions and Dust

Figure 9: Model subtraction of the near contemporaneous GALEX NUV grism observations of comet SW3, fragment B recorded on 2006-May-02. Models were fit independently with the model on the right brighter by $\sim 20\%$. At distances greater than $1 \times 10^4$, the residuals are near zero except in the direction of the ion tail. There is also a slight extension in the OH and CS distributions in the direction of the dust tail (see discussion in Machholz and Schwassmann-Wachmann 3 C NUV Residuals).
Figure 10: *GALEX* NUV grism observations of comet SW3, fragment C recorded on 2006-Apr-23 (left) and 2006-Apr-28 (right).
Figure 11: GALEX NUV grism observations of comet SW3, fragment C recorded on 2006-Apr-23 (left) and 2006-Apr-28 (right) after identical model subtraction. The model slightly over-subtracts in the upper right quadrant. Emission associated with dust emanating from the peak in the instrument response to the solar continuum is clearly seen. The extent of the dust emission detected by GALEX is $\sim 10^4$ km.
Figure 12: GALEX NUV grism observations of comet Tuttle recorded 2007-Dec-07 (left) and 2007-Dec-08 (right). The Dec-07 image shows the comet moving toward a source which was not well characterized by the GALEX pipeline and therefore not masked in our pipeline. On Dec-08, several sources were characterized but the masks were not wide enough (see dark lanes in sources). These effects can be easily taken out by hand masking.
Figure 13: *GALEX* NUV grism observations of comet Tuttle recorded 2007-Dec-07 (left) and 2007-Dec-08 (right) after subtraction of the 2-D model of coma emission from OH and CS described in the text. Despite the problems with source contamination, it is clear that the residuals are very close to zero except for a point source-like contribution at CS and a slight bow at OH. The OH residual indicates that an adjustment to our H$_2$O and OH scale lengths is likely needed.
Figure 14: *GALEX* NUV grism observations of comet Tuttle recorded 2007-Dec-10 (left) and 2007-Dec-11 (right). The Dec-07 image shows the comet moving toward a source which was not well characterized by the *GALEX* pipeline and therefore not masked in our pipeline. On Dec-08, several sources were characterized but the masks were not wide enough (see dark lanes in sources). These effects can be easily taken out by hand masking.
Figure 15: *GALEX* NUV grism observations of comet Tuttle recorded 2007-Dec-10 (left) and 2007-Dec-11 (right) after subtraction of the 2-D model of coma emission from OH and CS described in the text. The same production rate parameters are used on both days. The dust may be over-subtracted on the 10th.
Figure 16: *GALEX* NUV grism observations of comet Tuttle recorded 2007-Dec-26 (left) and 2008-Jan-01 (right).
Figure 17: Apparent in the Dec-26 image is a small extension on the CS residual which appears to be resolved dust emission. The Jan-01 observation was recorded when the comet had a heliocentric velocity of $-9.1 \text{ km s}^{-1}$. This is on a steep slope in the OH $g$-factor predicted by Schleicher & A’Hearn (1988). Material moving toward the Sun (up) is subject to a Greenstein (1958) effect brightening.
Figure 18: *GALEX* FUV grism observation of comet Tuttle recorded 2007-Dec-26 (upper left) and 2008-Jan-01 (upper right). The lower images show the model subtracted from the data. “Holes” in the FUV background are evident, but in general, the residual at large distances is reasonable (e.g., not over-subtracted). Images have been binned 10×10 to improve S/N.
Figure 19: GALEX FUV grism observation of comet Tuttle recorded 2007-Dec-26 (left) and 2008-Jan-01 (right) after model has been subtracted in two cases. In the top row, only C I has been subtracted. In the bottom row, both C I and S I have been subtracted. We used the relatively isolated S I 1815 Å feature as a guide. We may have over-subtracted the S I emission, which makes the detection of CO Fourth Positive emission all the more likely. The sunward extension in the emission of comet Tuttle on Dec-26 is seen in the NUV data as well.
Figure 20: Spectral cuts through the GALEX FUV grism observation of comet Tuttle recorded 2007-Dec-26 (left) and 2008-Jan-01 (right). Top row is the data, middle row is the data with C I emission subtracted, bottom row is the data with both C I S I emission subtracted. A case could be made that on Dec-26, S I is over-subtracted.
Figure 21: *GALEX* NUV grism observations of comet Lulin recorded 2009-Feb-20 (left) and 2009-Mar-06 (right). Bottom panels show cuts through the central 10 pixels of the images. The grism 1st order effective area ($A\Omega$) curve (dashed) and the solar continuum multiplied by $A\Omega$ (dotted) are also indicated. The box-shaped structures in the images are poorly masked background sources that are dispersed by the grism (left-right) and smeared by the fast motion of the comet (up-down). Masking will be improved in subsequent reduction efforts. Note that emission is clearly detected to cometocentric distances of $2 \times 10^5$ or twice the scale length of OH.
Figure 22: The data are not well fit by the model inside of $1 \times 10^5$ km. There is an obvious extension toward the dust tail extending well beyond the edges of the images. The appearance of the half-moon on Mar-06 is somewhat exaggerated by the over-subtraction of the model sunward at $\sim 1 \times 10^5$ km. This trough is roughly centered on the OH 3080 Å band and likely indicates a problem with the OH profile in this region. Machholz showed a reasonably good match to the model profile in this region which suggests a time variation in the production rate of Lulin. It should also be noted that the viewing geometry for Lulin was rather extreme: both the ion and dust tails were pointing into the sky plane. A simple $1/\rho$ dust coma is therefore not likely to provide a good match to the data. The heliocentric velocity of Lulin was also on a steep gradient in the OH $g$-factor, possibly implicating the Greenstein effect.
Figure 23: *GALEX* FUV grism observation of comet Lulin recorded on 2009-Feb-20 (left) and 2009-Mar-06 (right). Bottom panels show cuts through the central 10 pixels of the images. Note that the comet was significantly brighter on Feb 20. Extended C I emission is the dominant feature in this wavelength range.
Figure 24: GALEX FUV grism observation of comet Lulin recorded on 2009-Feb-20 (left) and 2009-Mar-06 (right) after model C I emission has been subtracted. There is a hint of S I emission evident in the spectral cuts, which we use as a guide to set upper limits to the S I emission.
Figure 25: GALEX FUV grism observation of comet Lulin recorded on 2009-Feb-20 (left) and 2009-Mar-06 (right) after model C I and S I emission have been subtracted. As with the NUV data, we do not find that it is possible to achieve zero residuals near the nucleus without over-subtracting at larger radii. Since dust does not contribute detectably at FUV wavelengths, this extended emission is due to a genuinely extended source, time variation, and/or problems with the CO and C I scale lengths we are using. Azimuthal symmetry in the emission argues against extended emission from a dust source.
Figure 26: GALEX FUV grism observation of comet Lulin recorded on 2009-Mar-6 after model C I and S I emission have been subtracted. Data have been binned 4×4. In this case, the C I production rate has been increased to $5 \times 10^{28}$ s$^{-1}$ in order to minimize the residuals at the comet nucleus. A clear asymmetry in the residuals is seen centered toward 1400–1600 Å. This residual is roughly axisymmetric, suggesting a coma feature. We have subtracted a simple Haser model of the S I coma features at 1425, 1475, and 1814 Å. The relative $g$-factors for these multiplets have been determined computationally as a function of heliocentric velocity (Feldman private communication 2009). The “hole” at 1814 Å and the fact that we do not account for S I optical depth effects suggests we have slightly over-subtracted the S I. Besides C I and S I, the CO Fourth Positive system is the only other major contributor to this band (e.g., Tozzi et al., 1998). Thus, we propose that we have detected CO Fourth Positive emission in comet Lulin to cometocentric distances of at least $1 \times 10^5$ km.
Acknowledgments

We would like to thank K. Foster for his help planning the GALEX comet observations, T. Conrow and the entire GALEX pipeline team for providing high quality products to work with and J. Giorgini and the JPL HORIZONS team for calculating high quality cometary ephemerides from the perspective of GALEX. GALEX is operated for NASA by the California Institute of Technology under NASA contract NAS5-98034. This work was supported as part of the GALEX Guest Investigator program.
References


