Wide-field spectroscopic observations of comet C/2004 Q2 (Machholz) by *GALEX*

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ABSTRACT

Comet C/2004 Q2 (Machholz) was observed by the Galaxy Evolution Explorer (*GALEX*), UT 2005 March 1. The *GALEX* satellite, a NASA Small Explorer (SMEX) mission, designed to map the history of star formation in the Universe (Martin *et al.* 2005), is also well suited to cometary coma studies because of its high sensitivity and large field of view. Improved spacecraft aspect information, recently made available to our Guest Investigator team has allowed us to accurately take out cometary motion and co-add all 4 orbits of grism observations. The resulting increase in S/N from previous analyses (Morgenthaler *et al.* 2005) and the availability of on-orbit calibration (Morrissey *et al.* 2005) allow us to establish preliminary production rates and scale lengths for the bright UV cometary features seen in the data. We use simple (Haser 1957) models, with scale lengths modified to emulate the vectorial model (Combi *et al.* 2004) to map coma emission from several species, including OH and CS in the NUV (175–310 nm) and C I in the FUV (135–175 nm). This work was supported by the *GALEX* guest investigator program.

GALEX Observations

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 (1350–1750 Å, 1750–2800 Å) and integrated field grism spectroscopy (10–20 Å resolution). The 1.2 degree FOV diameter and high sensitivity to extended sources makes *GALEX* ideally suited to cometary coma studies.

GALEX observed comet C/2004 Q2 (Machholz) UT 2005 March 1 for five ∼1300 s periods (Earth eclipses of the satellite) in grism mode and one ∼1300 s period in direct imaging mode. The comet had an integrated visual magnitude of ∼6 mag at this time. Figures 1–2 show an overview of the standard pipeline processed data we have received from the *GALEX* operations team. Comet emissions clearly fill a substantial portion of the FOV. The NUV grism mode observation clearly show the CS 2576 Å, and OH 3080 Å molecular bands. The FUV grism mode observations show C I 1657 Å and C I 1561 Å emission. Hints of fainter emission from other species in both bands are seen.

Close inspection of the images shows comet motion during each ∼1300 s exposure. This motion is roughly aligned with the grism dispersion direction. The comet clearly moves about 1/4 of the field during the entire set of observations, with the satellite re-centering the comet after the second eclipse. The *GALEX* team has provided us with time-tagged photon lists from which we can construct images in the rest frame of the comet. Using the astrometric position for each photon, a geocentric cometary ephemeris from the JPL Horizon's system and the *GALEX* spacecraft orbit solution from space-track.org, we can, in principle, reconstruct comet images with precise astrometry. Unfortunately, the absolute astrometry in the *GALEX* photon lists is not good. Subsequent pipeline processing, in the reference frame of the celestial sphere, achieves excellent absolute astrometry. We are working with the *GALEX* team to understand how to use this information to obtain absolute astrometry in the coordinate frame of the comet.

Data: direct-mode

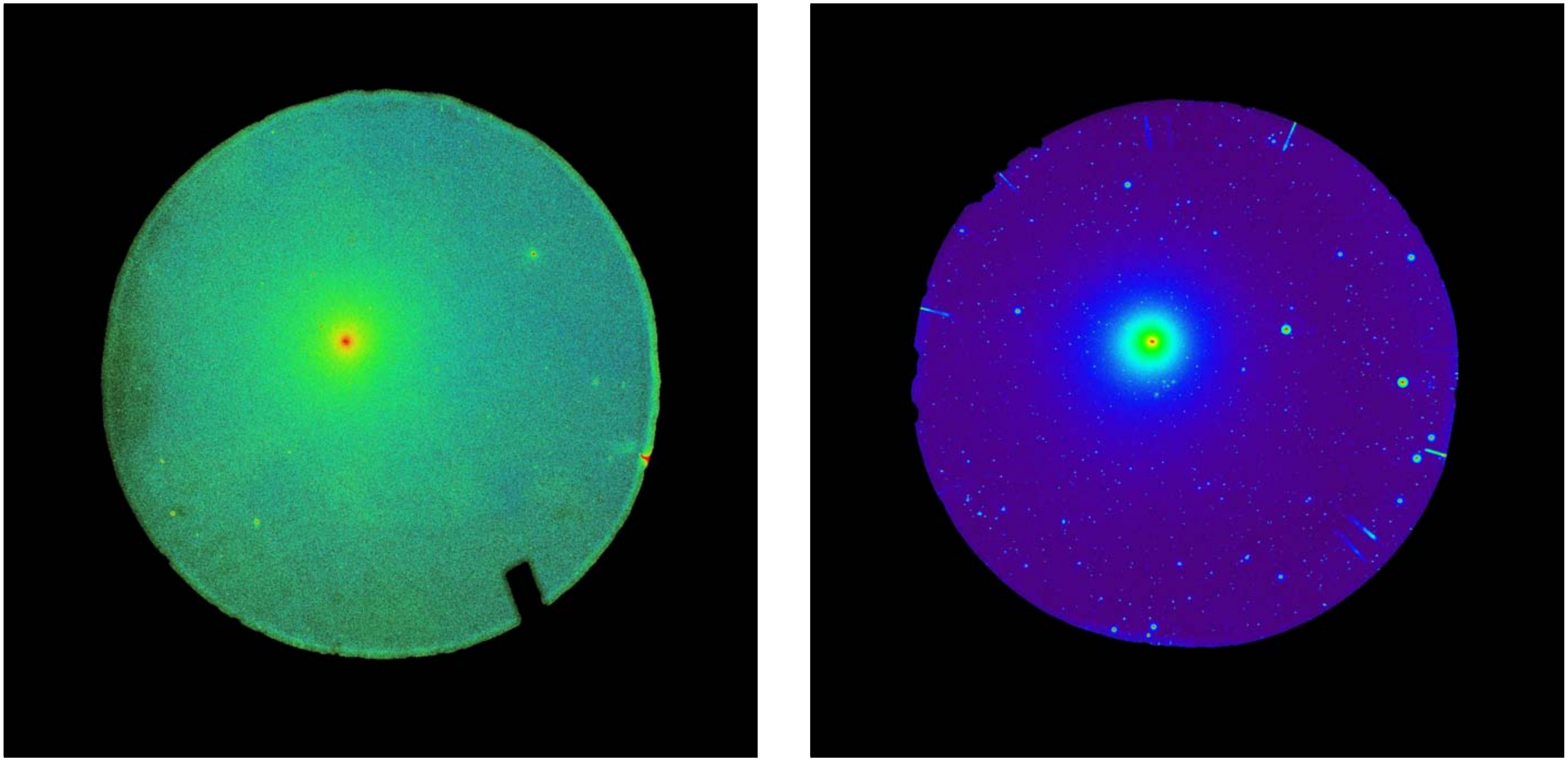

Fig. 1.— *GALEX* pipeline processed FUV (1350–1750 Å, left) and NUV (1750–2800 Å, right) direct images. Images are recorded simultaneously. FOV diameters are 1.28° and 1.24°, respectively.

Data: grism-mode

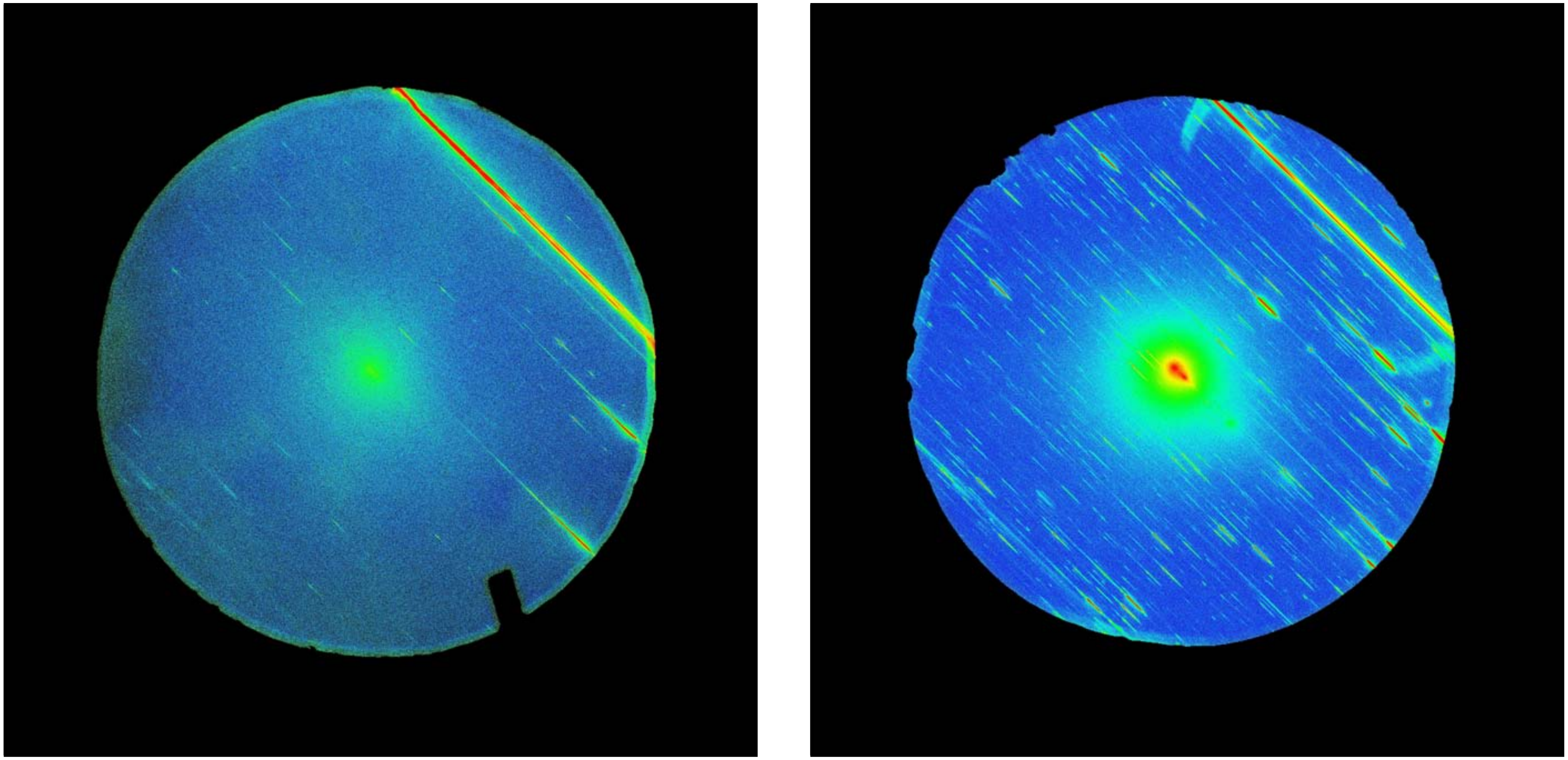

Fig. 2.— *GALEX* pipeline processed FUV (1350–1750 Å, left) and NUV (1750–2800 Å, right) grism images recorded 5 eclipses earlier than those in fig. 1. Brighter stars in the NUV image clearly show 0th, 1st, 2nd and 3rd order grism response (1st is brightest). 2nd order is most efficient in FUV. The dispersion runs from short wavelengths toward the lower lower right to longer wavelengths toward the upper left. The other 4 sets of grism images are similar but with the stars in slightly different positions as the comet moves across the sky.

Reduction and Analysis Strategy

Experimentation with the *GALEX* data and data from similar experiments (where the instrument response matrix is highly non-diagonal) suggests that the maximum information can be extracted from the data by constructing a model of the emission incident on the instrument, convolving that model with the instrument response, and comparing the results to the recorded data. Experience shows that the more parameters that can be constrained ahead of time (e.g. the background level can be fixed to the median value of the image), the better the chance for achieving a convergent fit to the comet emissions. Currently, the astrometric position of the comet and the comet emission are correlated and convergence has not been achieved.

Experimentation has also shown that the stellar spectra influence the fits to the cometary emission. Using the standard *GALEX* pipeline products, it should be possible to construct a mask of the stellar emission. As the comet moves through the star field, masked emission could be filled in, creating a star-free, comet image. Production of such an image would require a deeper understanding of the *GALEX* pipeline than we currently possess. In the pursuit of this understanding, we are likely to find the solution to the absolute astrometry problem. Until we effectively mask the stars from different eclipse visits, co-adding grism exposures only increases background problems.

We need to understand the standard *GALEX* pipeline products and processing better to get the most out of our cometary data

FUV and NUV grism data in detail

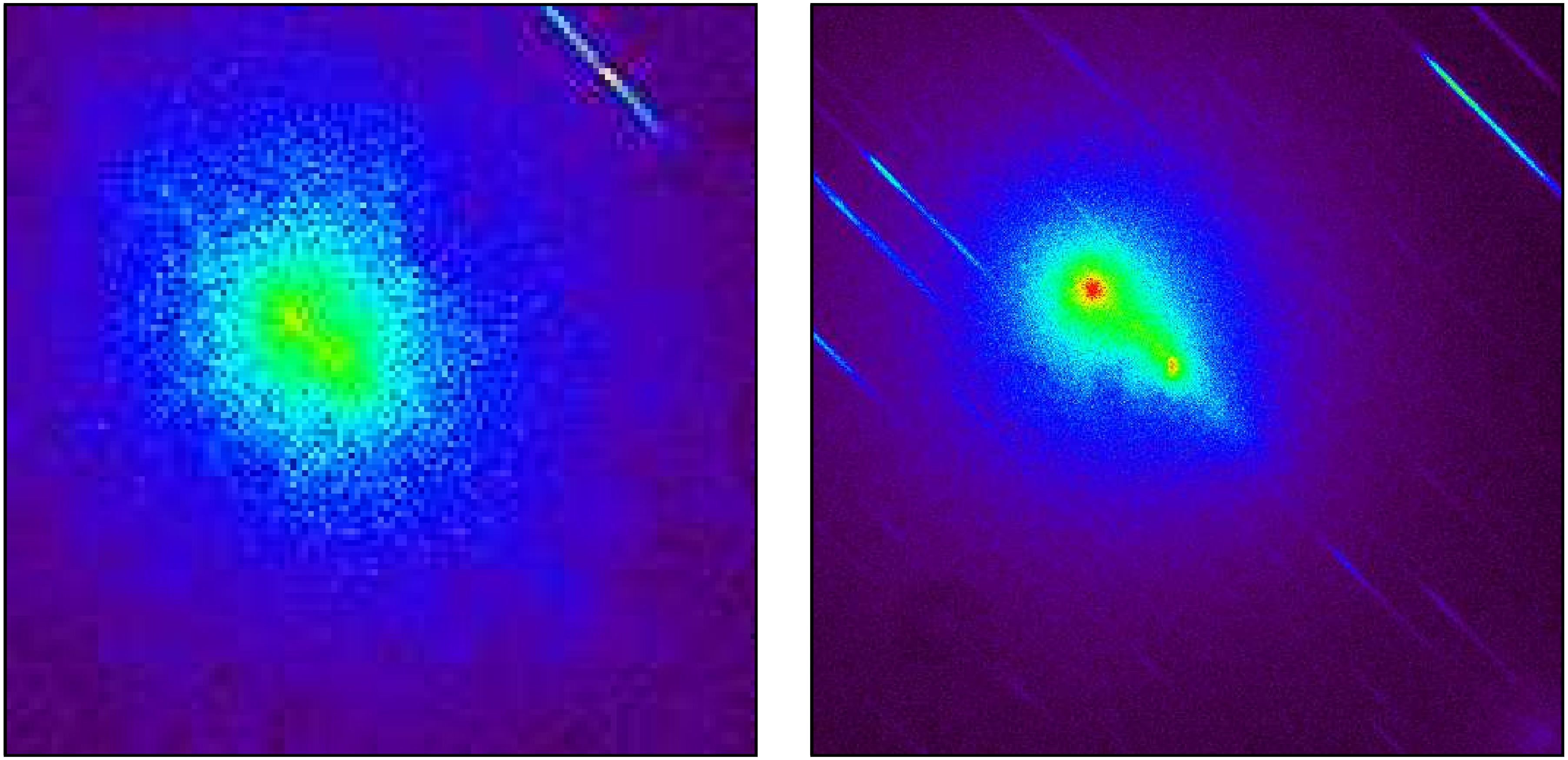

Fig. 3.— Close-up FUV (left) and NUV (right) grism images with comet motion taken out. The FUV grism image (binned 4×4 to improve signal) shows C I 1657 Å and C I 1561 Å emission. The NUV image clearly shows the OH 3080 Å and CS 2576 Å molecular bands. Upon subtraction of residuals, hints of fainter emission from other species in both bands are seen.

Subtraction of FUV C I, S I and CO comas

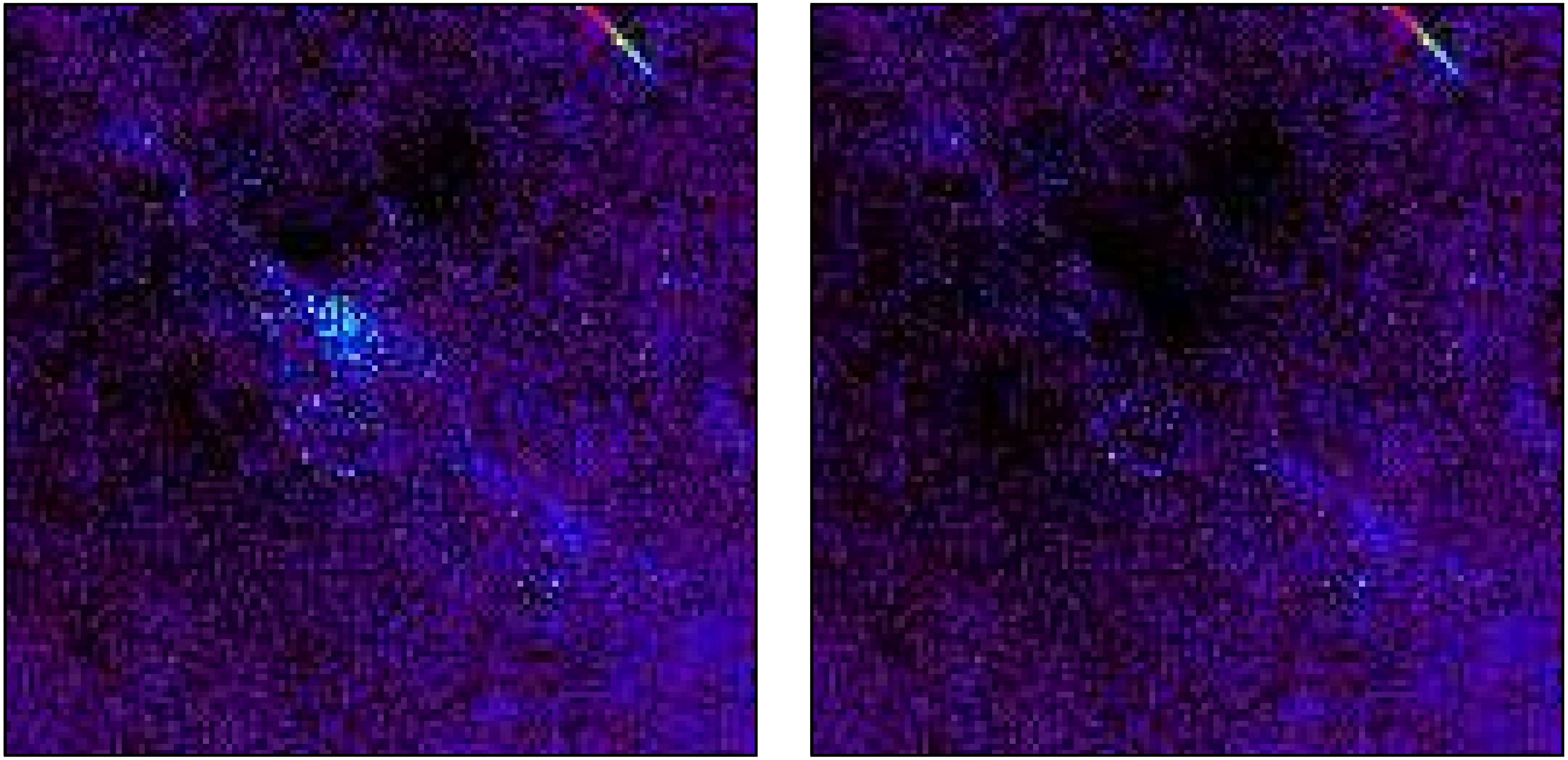

Fig. 4.— *GALEX* first grism eclipse FUV grism data with model C I 1657 Å and C I 1561 Å emission subtracted out (left). Residual emission, subtracted in the right-hand image seems well described by two lines, emulating the S I and CO complexes at 1475 Å and 1510 Å, respectively (e.g. Feldman *et al.* 2004). Non-uniformity in the background, potentially removable using standard *GALEX* pipeline products, make more quantitative analysis of these FUV data difficult.

NUV Comet Model

Preliminary analysis (Morgenthaler *et al.* 2005) shows the bright molecular bands at OH 3080 Å and CS 2576 Å are present in the NUV grism images. For these analyses, we have constructed a model using lines at OH 3080 Å and CS 2576 Å to emulate the wide molecular bands centered at these wavelengths. According to Schleicher & A'Hearn (1988), emission in the OH 3080 Å band at a heliocentric velocity of 11 km s^{-1} implies emission in the OH 2826 Å band a factor of 15.6 less intense. We add emission at this wavelength and CS emission at 2663 Å and 2507 Å, factors of 0.14 and 0.036 down from the CS 2576 Å band (Smith *et al.* 1980). We also added a spherical dust coma with a radial fall-off of r^2 and a somewhat arbitrarily set $Af\rho$ value of 300 cm.

The radial distribution of our OH comas is given by the two-component Haser (1957) model described by Combi *et al.* (2004). The parent species of OH is $\mathrm{H_2O}$ whose outflow velocity is typically assumed to be $V_{\mathrm{H_2O}} = 0.85R^{-1/2}$ km s^{-1} (Budzien *et al.* 1994), where R is the heliocentric distance of the comet. The OH outflow velocity is calculated for a given $V_{\mathrm{H_2O}}$ assuming an isotropic OH ejection velocity of 1.05 km s^{-1} (Crovisier 1989) and the prescription of Combi *et al.* (2004).

We found, unexpectedly, that using this prescription, which resulted in $\mathrm{H_2O}$ and OH outflow velocities of 0.7 and 1.2 km s^{-1}, respectively, did not result in a good match to the data. Using $V_{\mathrm{H_2O}} = 0.58R^{-1/2}$ km s^{-1} (Delsemme 1982; Bockelée-Morvan *et al.* 1990), which results in outflow velocities of 0.5 and 1.1 km s^{-1}, a much better match was achieved.

The origin of CS is not well know in comets. For these analyses, we assume the parent of CS is $\mathrm{CS_2}$ and $\mathrm{CS_2}$ has a lifetime of 1000 s (Feldman *et al.* 1999). Smith *et al.* (1980) estimated the lifetime of CS to be 42,000 s for comet West for $R = 0.52$ AU. Because of their short scale lengths, we set the outflow velocities of $\mathrm{CS_2}$ and CS equal to that of water.

Subtraction of NUV OH and CS comas: fast or slow H_2O outflow?

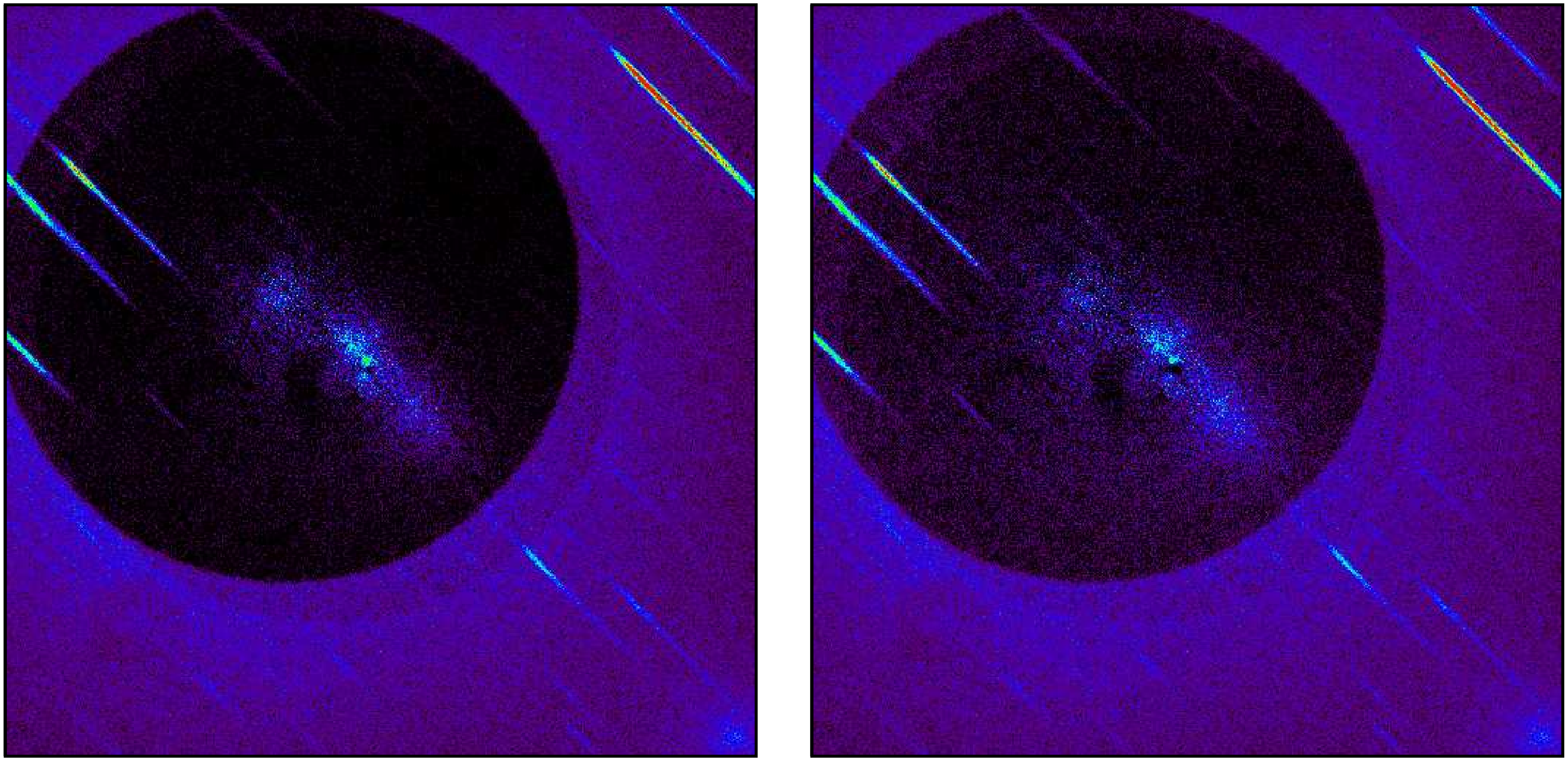

Fig. 5.— *GALEX* first grism eclipse NUV grism data with model OH 3080 Å, 2826 Å and CS 2576 Å, 2663 Å and 2507 Å comas subtracted. Model is calculated to a radius of 300″ (170,000 km). Color scale is the same in both figures, linear with dark purple approximately 0, black is negative. On the left $V_{\mathrm{H_2O}} = 0.85R^{-1/2}\,\mathrm{km\,s^{-1}}$ (Budzien *et al.* 1994) and Q(OH) = $1 \times 10^{29}\,\mathrm{s^{-1}}$. On the right, $V_{\mathrm{H_2O}} = 0.58R^{-1/2}\,\mathrm{km\,s^{-1}}$ (Delsemme 1982) and Q(OH) = $7 \times 10^{28}\,\mathrm{s^{-1}}$. **The model on the left clearly over-subtracts the extended emission.** Some of the residual emission around CS feature (lower right) may be due to approximations in the ephemeris and lack of absolute astrometry.

Discussion

Using the prescription given in Combi *et al.* (2004) to convert physical outflow velocities and isotropic photochemical ejection velocities to Haser scale lengths, Figure 5 shows that the previously discounted “slow” $\mathrm{H_2O}$ outflow velocity of Delsemme (1982) fits the data better than the more current value recommended by Budzien *et al.* (1994). The effect is not that noticeable inside 60,000 km, where neither model necessarily fits the data well (there may be other emission lines not accounted for). Outside 60,000 km, however, beyond the region typically studied by long-slit spectrometers or narrow-band photometers, the difference in the models is very clear. The superiority of the “slow model” fit over the “fast model” continues to the edge of the 1.24° *GALEX* FOV.

Word of warning: coma models are typically compared to radial profiles of narrow-band images or long-slit spectra on *log-log* plots. The *GALEX* objective grism spectroscopy creates overlapping comas, which make such a presentation difficult. We instead show a residual image (model minus data) stretched on a linear scale. Once the data are cleaned of stars and other background issues, χ^2 minimization procedures should work very well, but until then “chi by eye” attempts should be taken with a grain of salt.

Until we obtain better absolute astrometry, it is very difficult to make statements about the short-lived species, CS.

The FUV data will clearly benefit from co-adding the observations. However, for the best results, we must first effectively mask stars and apply the *GALEX* pipeline relative response (flatfield) and background corrections.

Things to Do

- Extract absolute astrometry from *GALEX* pipeline products (it is in there somewhere!)
- Use satellite orbit from space-track.org to create a high-precision comet ephemeris
- Mask out stars as comet image is being created
- Apply flatfield and background corrections
- Co-add exposures
- Use individual lines in molecular bands rather than emulating whole band with one line
- Use more sophisticated coma models to generate emission profiles

With these reduction and modeling goals accomplished, we will use our technique of simultaneous multi-coma modeling, possibly in conjunction with other data, to constrain the CS and C I parentage/scale length problems and she light on the question of the OH profile. With the bright lines well described, the S/N may be sufficient to probe the nature of the fainter emissions in these bandpasses.

Acknowledgments

We would like to thank K. Foster for his help planning the Machholz observations and T. Conrow and the *GALEX* pipeline team for doing a great job on the spacecraft aspect reconstruction. *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* Cycle 1 Guest Investigator program.

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