

Wide-field spectroscopic observations of comets in the UV: GALEX observations of C/2004 Q2 (Machholz)

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ABSTRACT

We report on UV observations of comet C/2004 Q2 (Machholz) made UT 2005 March 1 with the GALEX spacecraft. Several lines in the UV, including the C I 1561/1657 Å multiplet and the CS 2576, and OH 3080 Å molecular bands are easily detected to angular separations of >20 arcmin (200,000 km) from the nucleus. We present preliminary analyses that show that with the bright emissions removed, other distinct features are detectable. Our efforts encourage us to improve upon the standard GALEX pipeline processing, enabling us to make positive identifications of the emissions and estimate values for production rates and scale lengths.

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. In the NUV grism mode observation, at least two distinct coma features are resolvable. We show that these features are consistent with the CS 2576 Å, and OH 3080 Å molecular bands. Because the GALEX sensitivity is not well known at 3080 Å (fig. 3), it is not possible to estimate the OH production rate from our data at this time. CS clearly blends with other emission, making determination of its production rate and scale length difficult. Proper interpretation of these data depends on *a priori* knowledge of the emission wavelengths and reasonable constraints on the coma scale lengths for each species.

Data: direct-mode

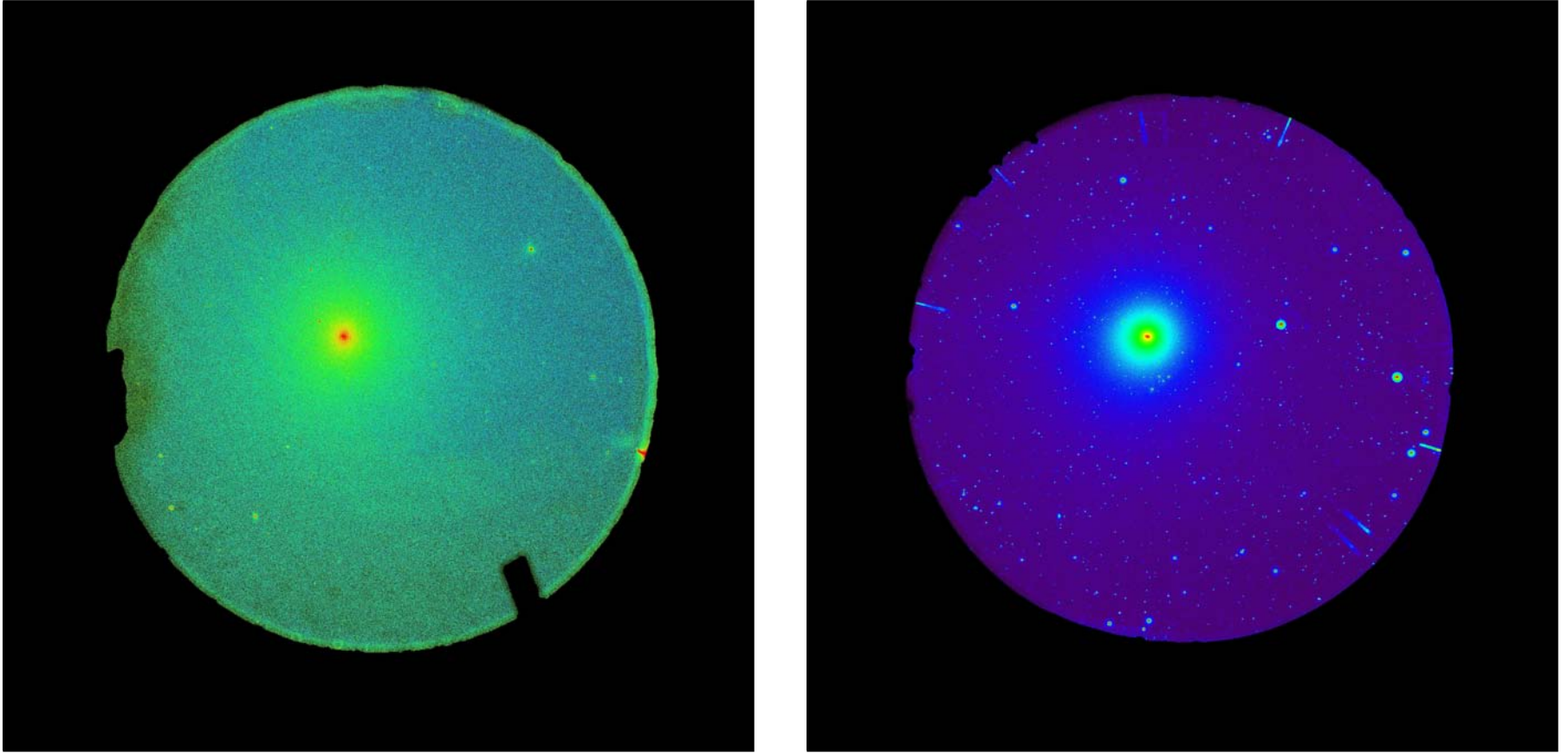


Fig. 1.— GALEX pipeline processed FUV (1350–1750 Å, left) and NUV (1750–2800 Å, right) direct images. Images are recorded simultaneously. FOV diameters are 1.28° and 1.24° , respectively.

Data: grism-mode

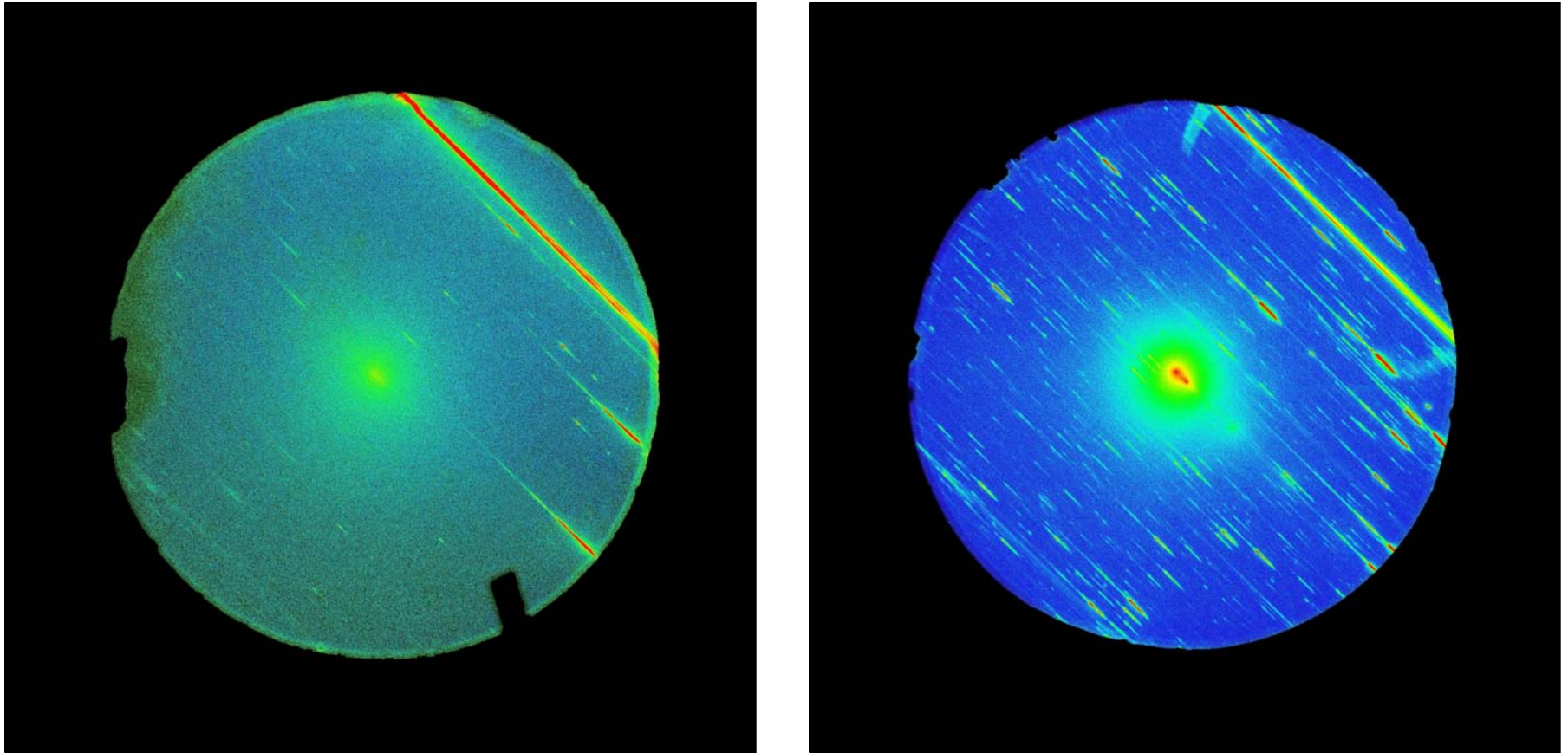


Fig. 2.— GALEX pipeline processed FUV (1350–1750 Å, left) and NUV (1750–2800 Å, right) grism images recorded 5 eclipses earlier than those in fig. 1. Brighter stars in the NUV image clearly show 0th, 1st, 2nd and 3rd order grism response (1st is brightest). 2nd order is most efficient in FUV. The dispersion runs from short wavelengths toward the lower lower right to longer wavelengths toward the upper left.

Data: detection efficiency

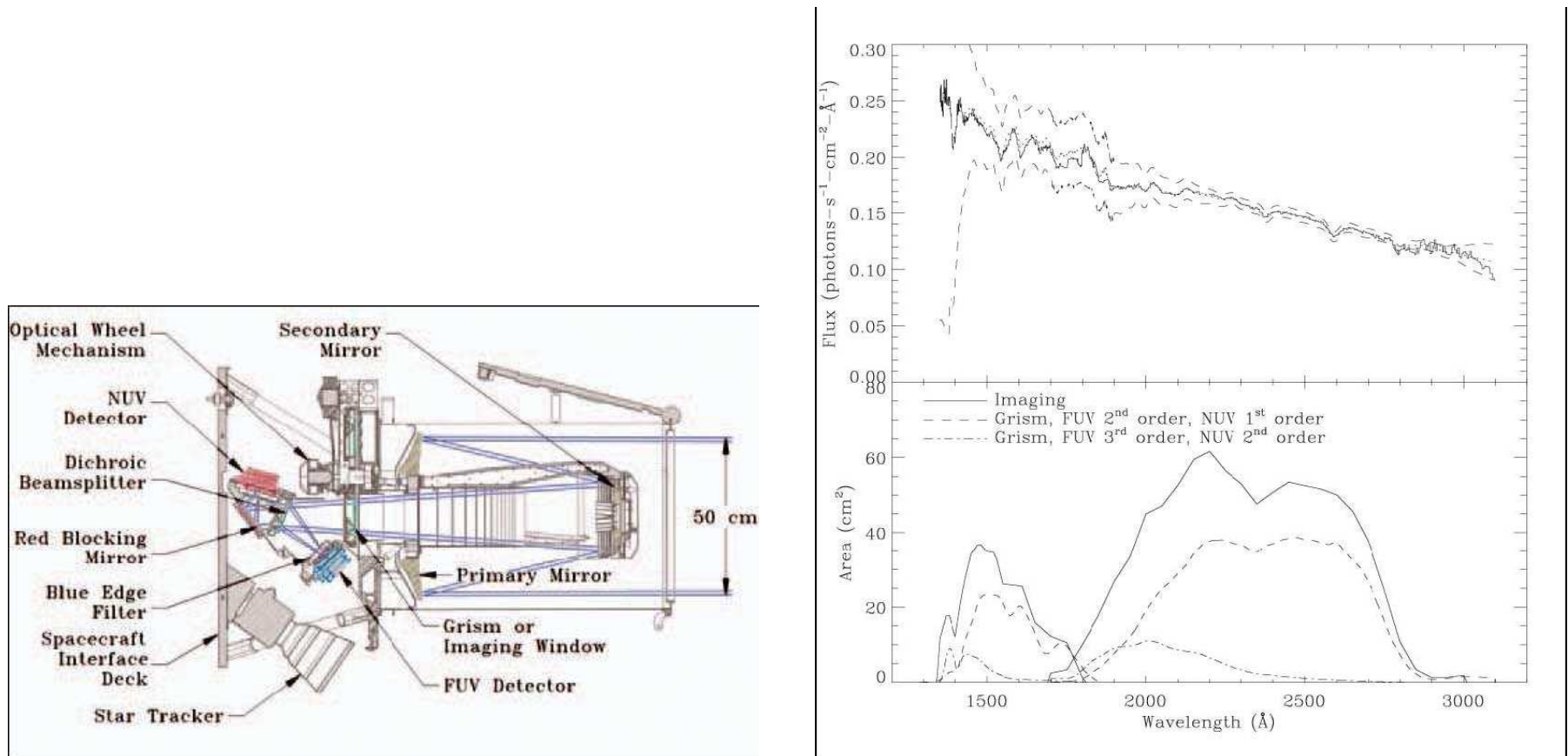


Fig. 3.— GALEX instrument (left) and effective area curves (right) (Morrissey *et al.* 2005, figs 1, 3). Upper panel: A composite of 42 240 s GALEX spectra of a standard white dwarf (solid). The HST reference spectrum (dotted). The range of 1σ variations among the 42 spectra (dashed). Lower panel: The ground-measured imaging-mode effective area (solid). The flight-measured grism-mode effective area (dashed). The additional effective area in the grism 2nd (NUV) and 3rd (FUV) orders (dot-dashed). Note arbitrary cutoff $>3000 \text{ \AA}$.

Reduction strategy

We recently received the time-tagged photon event files for the Machholz observations from the GALEX operations team. The files contain a preliminary spacecraft aspect solution which allows reconstruction of images in the comet frame of reference. A known problem with the GALEX spacecraft is that this preliminary aspect solution is not always of high quality. Using the stellar spectra in the NUV image, we will double-check the aspect solution. During at least one eclipse (possibly three), there was a substantial “bobble” of several arcseconds in the spacecraft aspect that we should be able to correct.

Once the spacecraft aspect solution is corrected, we will need to apply a correction to the standard JPL “Horizons” ephemeris, since the comet, at a geocentric distance of 0.8 AU has $\sim 8''$ parallax during a limb-to-limb earth orbit. We may be able to correct both effects in one step by measuring the centroid of the CS and/or OH emissions for several time slices per eclipse.

For these preliminary analyses, we used the standard JPL ephemeris and the supplied spacecraft aspect solution to “freeze” the comet for one of the cleaner eclipses (our first grism eclipse).

Analysis strategy

Rather than try to reduce the data somehow to 1D spectra, our strategy for getting the most out of this dataset is to create 2D images that match the data. For these preliminary analyses, we use the (Haser 1957) model to generate 1D profiles for each of the known bright UV emissions (e.g. OH 3080 Å and CS 2576 Å for the GALEX NUV passband and C I 1657 Å and C I 1561 Å in the FUV; Festou & Feldman 1987). The models are generated with point spacing that matches the GALEX pixel size (1."5). Using the expected comet center, line wavelength, and the GALEX dispersion relation, we find the point about which a 2D version of this profile will be centered. We then use the distance between the center of each pixel in the output image and this point to interpolate the 1D profile and create a model 2D coma. This model coma is then multiplied by the GALEX effective area–solid angle product ($A\Omega$) and smeared by the GALEX PSF.

The entire model coma system is implemented in a such a way as to be the kernel function of a non-linear least-squares curve fitting routine (MPFIT, implemented in IDL). Coma emission lines at arbitrary wavelengths can be easily added and there is code to model dust emission, though we find it to be negligible for Machholz at these wavelengths. The system allows for an automatic search for a minimum in χ^2 as parameters, such as the production rate and Haser scale lengths, are varied. In practice, we find that the background stars will have to be masked out and more coma lines modeled for an automatic χ^2 minimization to yield meaningful results.

Subtraction of OH 3080 Å and CS 2576 Å

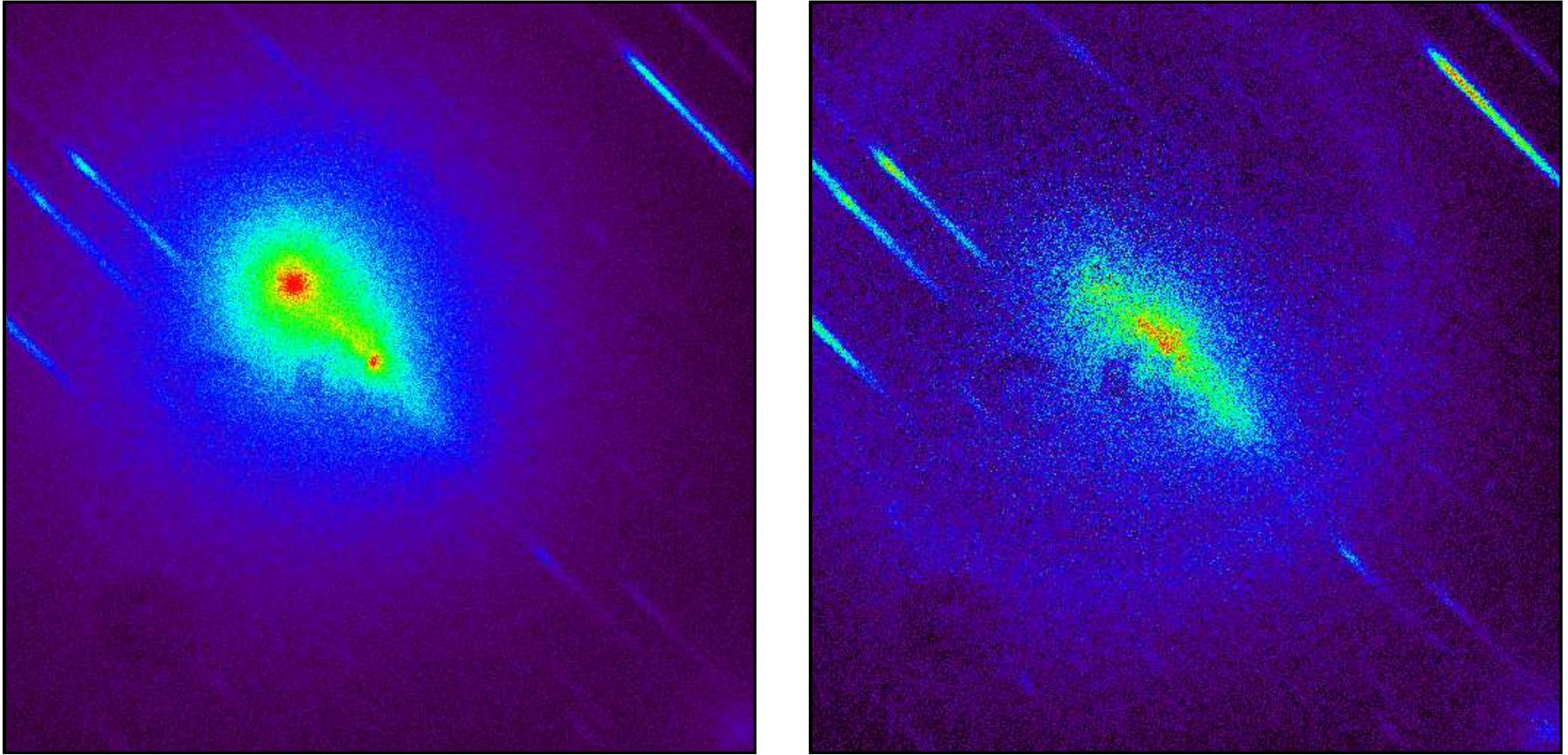


Fig. 4.— Preliminary reduction of GALEX first eclipse NUV grism data (left), with model OH 3080 Å and CS 2576 Å comas subtracted (right). Intensity scaling linear, with the **residual image scale twice as sensitive**. “C” shaped shadows are exposure dropouts from hot detector pixels which will be corrected in subsequent processing. Coma models calculated out to 200 pixels (clearly needs to be larger for OH).

Subtraction of C I 1657 Å and C I 1561 Å

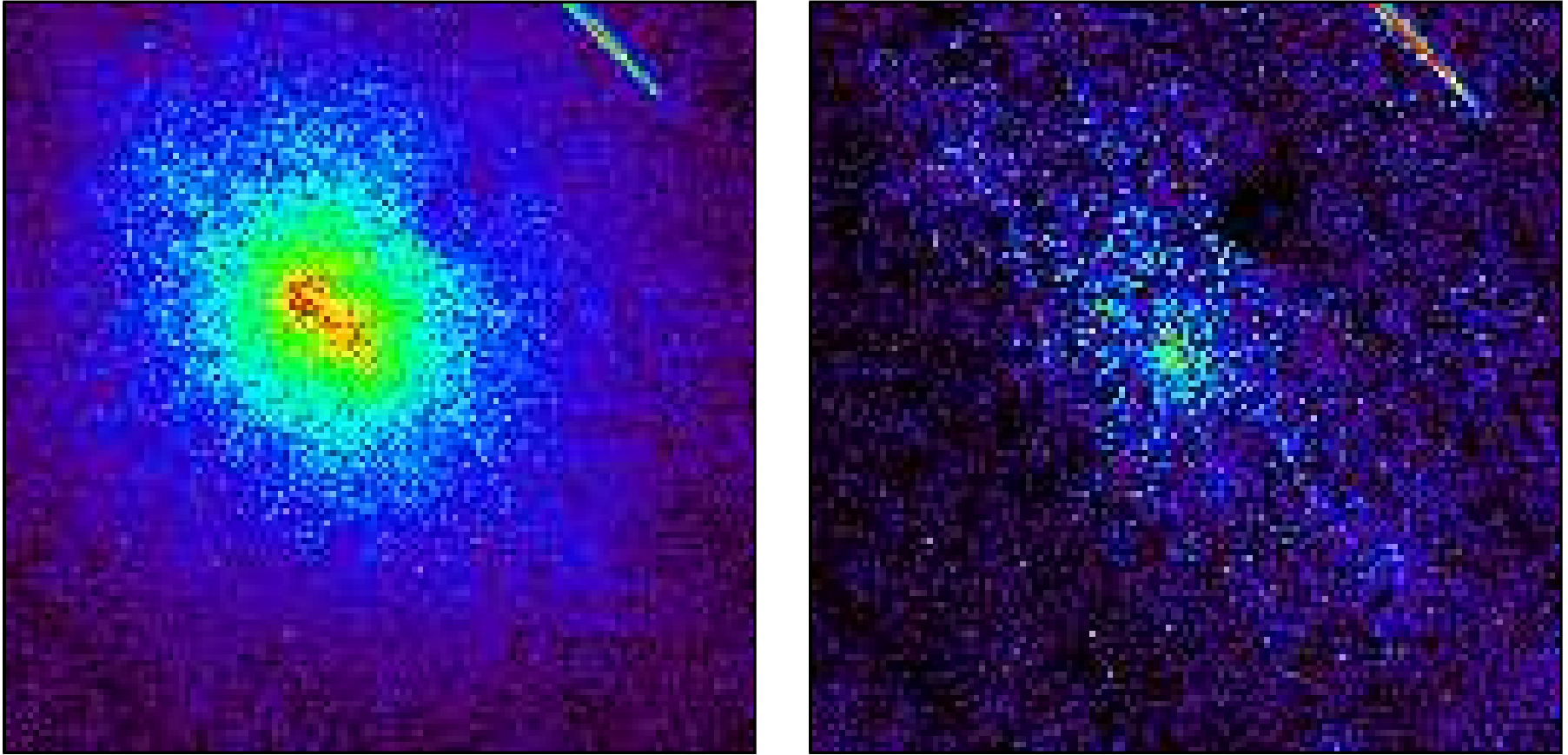


Fig. 5.— Preliminary reduction of GALEX first eclipse FUV grism data (left), with model C I 1561 Å and 1657 Å comas subtracted (right). Intensity scaling linear, with the **residual image scale twice as sensitive**. The data have binned 4×4 to improve signal. Residual image shows clear evidence for emission to the blue of C I 1561 Å.

Subtraction of S I 1475 Å and CO 1510 Å

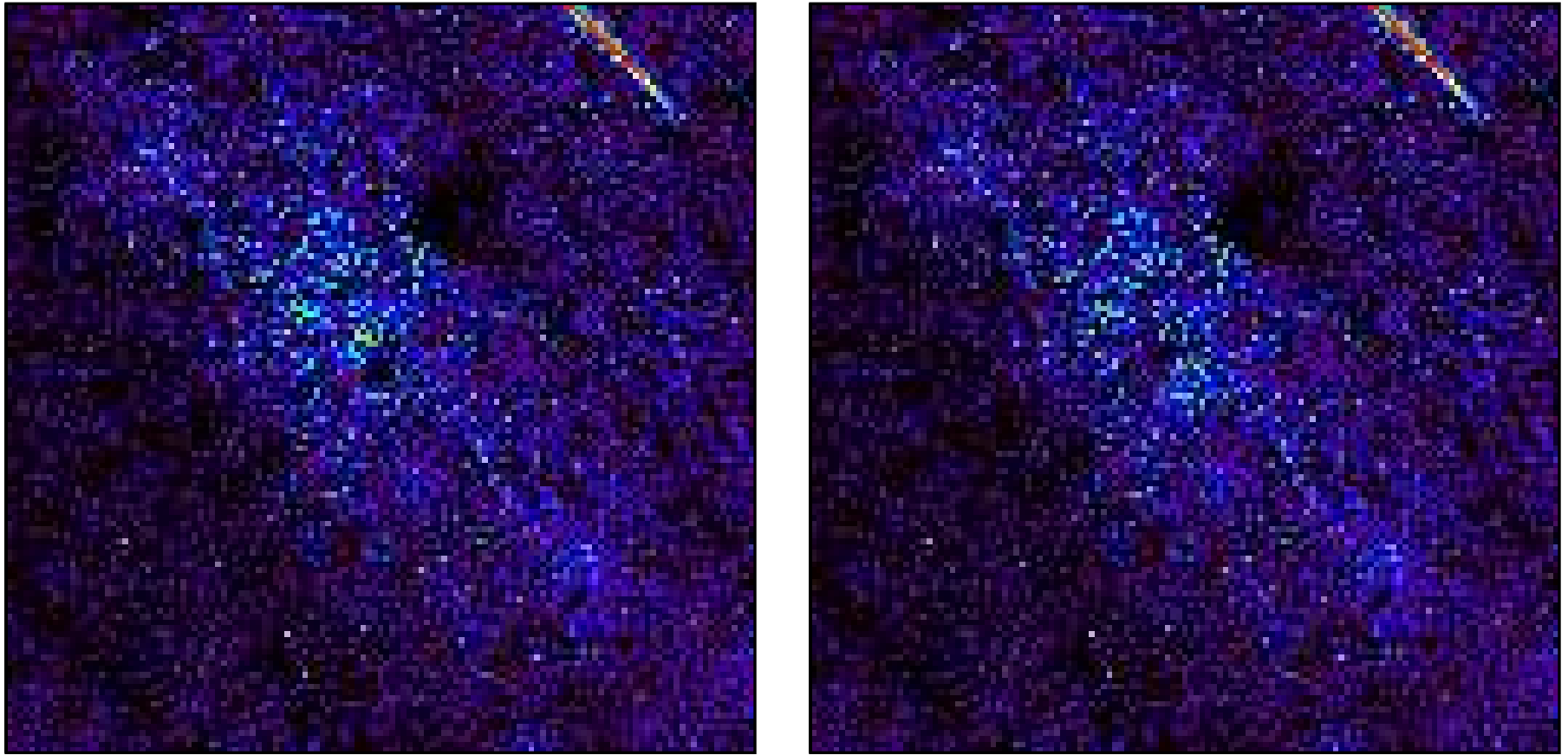


Fig. 6.— Similar to the right panel of Figure 5 but with one additional line subtracted: S I 1475 Å (left) and one of the brighter lines (1510 Å) from the CO ($A^1\Pi - X^1\Sigma^+$) band (right).

Discussion

These data show the strength and weaknesses of objective grism spectroscopy. Strength: emission out to several scale lengths from various comas are visible. Weakness: at sufficiently large distances the comas overlap and are not easily separable. By creating 2D model comas of the brightest expected emission lines and convolving them with the instrument response function, we show that weaker emission is detectable “underneath” the stronger lines. Complete reduction of the GALEX Machholz data outlined below will **increase our signal by approximately a factor of five.**

- spacecraft aspect solution
- precision Machholz ephemeris from perspective of satellite
- pixel-to-pixel exposure time variations
- star masking
- GALEX sensitivity above 3000 Å

With a complete dataset we will then 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.

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REFERENCES

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