

Ultraviolet Molecular Hydrogen Fluorescence in IC 63: *FUSE*, *HUT*, and Rocket Observations

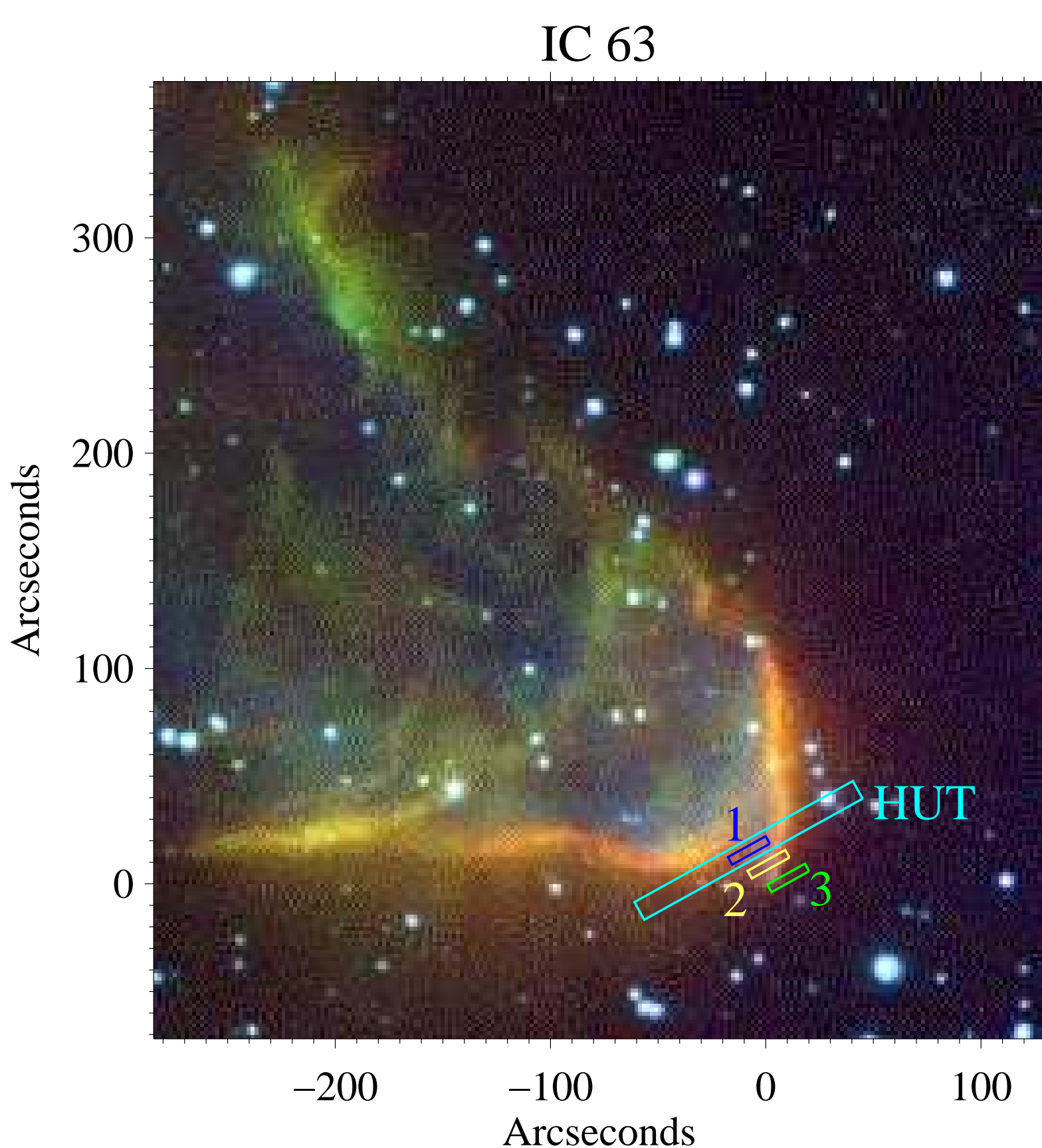
Kevin France, B-G Andersson, Stephan R. McCandliss, and Paul D. Feldman (JHU)

Abstract

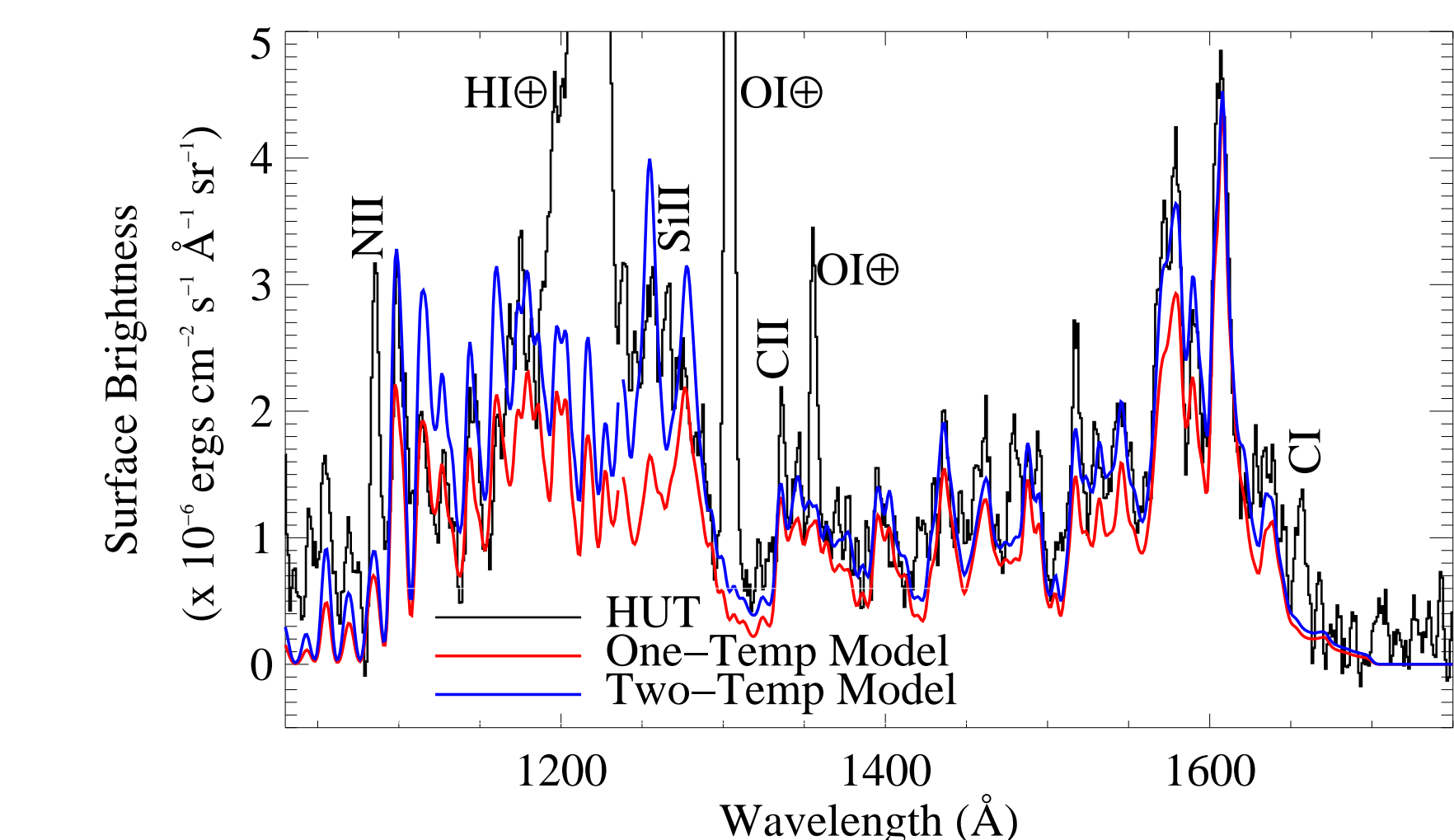
We present far-ultraviolet observations of IC 63, an emission/reflection nebula illuminated by the B0IV star γ Casiopeia located 1.3 pc from the nebula. IC 63 was the first reflection nebula in which molecular hydrogen fluorescence was detected and has previously been studied in both the mid-UV (*IUE*) and far-UV (*ORFEUS*). Here we present *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) observations towards three locations in the nebula, complemented by Hopkins Ultraviolet Telescope (*HUT*) data on the central nebular position and sounding rocket data on the stellar spectrum of γ Cas. Molecular hydrogen fluorescence is detected in all three *FUSE* pointing, but the intensities of this emission as well as the contributions from other species are seen to vary with position. The broad spectral coverage of the sounding rocket data (900–1590 Å) allows us to reliably predict the radiation field incident on IC 63. We use these data to test models of the fluorescence process. Our modeling resolves the perceived discrepancy between the existing mid and far ultraviolet observations and achieves a satisfactory agreement with the H_2 rotational structure observed with *FUSE*.

Fluorescent Molecular Hydrogen in Interstellar Clouds

Fluorescent ultraviolet emission is second step in the process that gives rise to the well studied near-infrared emission spectrum of photo-excited molecular hydrogen (H_2). These infrared emission lines are a commonly used diagnostic of the molecular gas phase of many classes of astronomical objects. The ultraviolet emission from molecular hydrogen was first predicted to be detectable in diffuse objects by Duley and Williams (1980). Witt et al. (1989) detected this emission in IC 63 with the Short Wavelength Primary camera on *IUE*, the first detection of this fluorescence spectrum pumped by a continuum source. Luhman et al. (1997) reported the detection of the near-infrared emission spectrum of fluorescent H_2 , making IC 63 the first (and only published) object seen to exhibit both the ultraviolet and infrared emission excited by ultraviolet continuum photons. Hurwitz (1998) presented the first spectrum of IC 63 below the *IUE* bandpass, using the Berkeley Extreme and Far-ultraviolet Spectrograph aboard *ORFEUS-II*. In this poster, we present the results of *FUSE* observations of IC 63, where we detect the fluorescent emission from H_2 and resolve the lines into their individual rotational components. These results mark only the second time that continuum-pumped fluorescence has been resolved below 1150 Å (France et al. 2004). Additionally, we use archival *HUT* data to test a model of fluorescent emission across the entire 912 – 1650 Å band spanned by the electronic transitions ($B^1\Sigma_u^+ - X^1\Sigma_g^+$ and $C^1\Pi_u - X^1\Sigma_g^+$) of H_2 (Figure 1).



IC 63 is a bright emission/reflection nebula illuminated by the hot star γ Cas (HD 5394), a lightly extinguished B0.5 IV ($E_{(B-V)} = 0.03$; Hurwitz 1998). Assuming that the star and the nebula are coplanar at a distance of ≈ 200 pc, the optical edge of the nebula is 1.3 pc from the star. There exists in the literature a number of arguments for fluorescent pumping from the ultraviolet continuum of γ Cas as the process giving rise to the observed H_2 emission (Witt et al. 1989; Luhman et al. 1997; Hurwitz 1998). Witt et al. (1989) present calculations of the energy budgets for competing processes such as a collisional excitation from a stellar wind or non-thermal excitation from electrons produced by stellar X-rays, and find that these explanations are insufficient to reproduce the nebular brightness observed in IC 63. The infrared H_2 line ratios seen by Luhman et al. (1997) are consistent with fluorescence rather than collisional excitation. Hurwitz (1998) discounts the possibilities of shocks by the narrow line widths seen in sub-mm molecular observations (Jansen et al. 1994), and we note that ultraviolet emission from H_2 cannot be excited thermally, the molecules would be dissociated before the upper electronic states could be populated.



FUSE Observations of IC 63

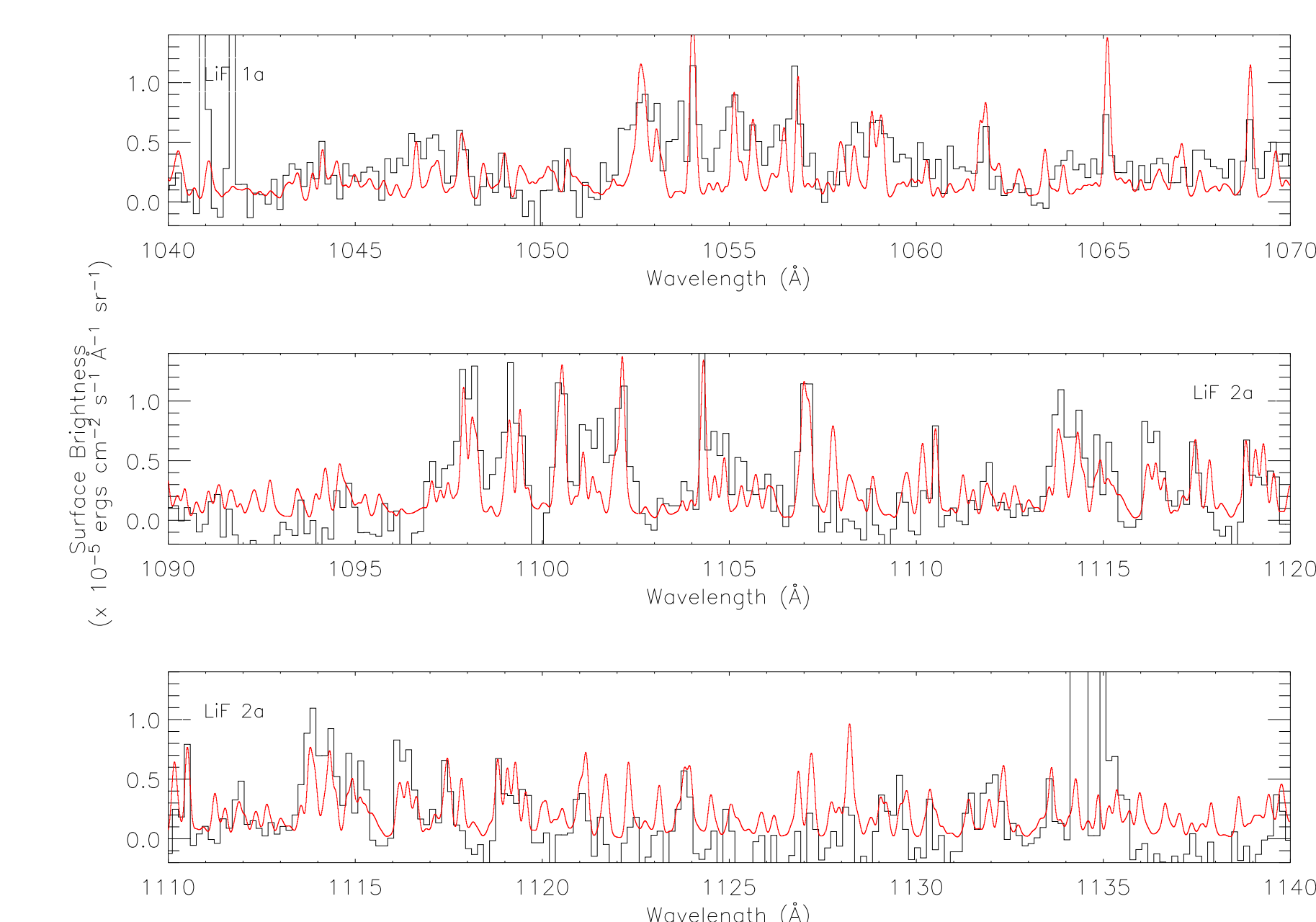


Figure 2. A sample of the *FUSE* MDRS spectra of IC 63. These 30 Å windows show the strongest emission bands at the POS2 pointing where the background subtraction was cleanest. The fluorescent emission model described below is overlaid.

IC 63 was observed by *FUSE* on 2001 September 09 and 10. The ($4'' \times 20''$) MDRS aperture was used at three positions in the nebula, as illustrated above. The data were obtained in time-tagged (TTAG) mode and have been reprocessed using the CalFUSE pipeline version 3.0.2. POS1 was observed for 15.9 ks, it is located in the bright “bullet-tip” of IC 63 and was chosen to overlap previous detections of ultraviolet fluorescence made by *IUE*, the Berkeley Extreme and Far-UV Spectrometer, and *HUT* (Witt et al. 1989; Hurwitz 1998; this work). POS2 is located along the limb of the bright optical emission, and was observed for 17.6 ks. POS3, observed for 31.5 ks, samples the region just outside the optical nebula. We detect fluorescent H_2 clearly at POS1 and POS2, and there is a tentative detection at POS3. The strongest molecular hydrogen line complexes are centered on 1055, 1100, 1115, and 1161 Å. $C\text{ II}^* \lambda 1037$ and $N\text{ II}^* \lambda 1085$ are seen strongly at all three positions, and $N\text{ II} \lambda 916$ is seen more weakly in the SiC 1B channel. Curiously, we do not detect $C\text{ II} \lambda 1036$ at any pointing in IC 63, although it should have been detectable assuming it will be roughly half as strong as $\lambda 1037$, we attribute this to self-absorption within the nebula. We find a similar behavior in the $N\text{ II} \lambda 1084/5$ and $S\text{ III} \lambda 1012/15/21$ ions.

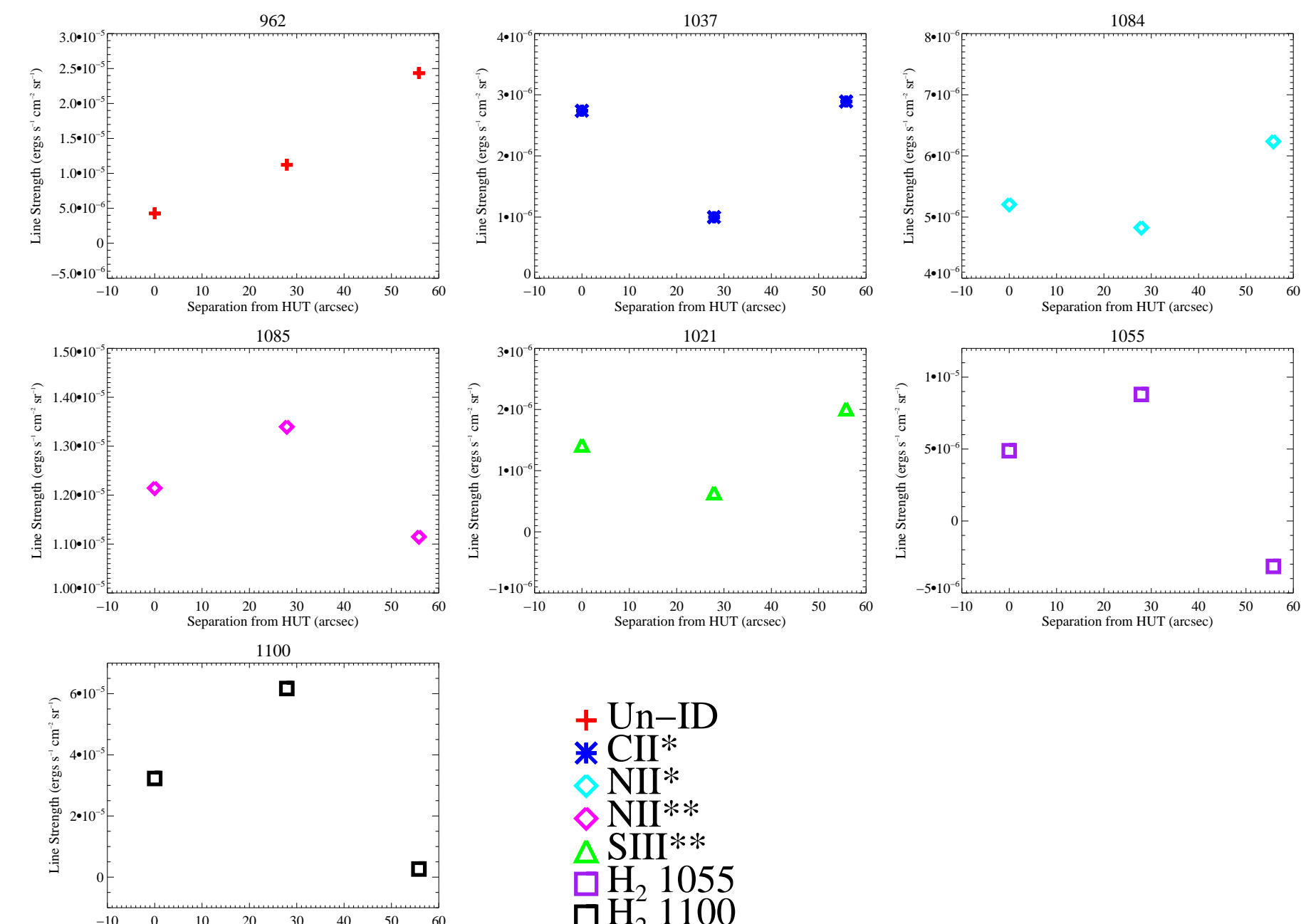


Figure 3. Line strength variations with distance measured from the *FUSE* spectra. The ionic and the molecular lines show an inverse relationship (with the exception of $N\text{ II}^* \lambda 1085$).

Fluorescent Molecular Hydrogen Model

Synthetic spectra of fluorescent emission from molecular hydrogen can be made by treating the object of interest as a plane-parallel slab, calculating the radiative transfer during the fluorescence process. Such models assume a ground electronic state population, then use photoexcitation cross sections and an incident radiation field to calculate the rovibrational levels of the upper electronic state ($B^1\Sigma_u^+$ and $C^1\Pi_u$). The molecules will then return to the ground electronic state following the appropriate selection rules and branching ratios, producing the observed ultraviolet emission lines and leaving the molecules in excited rovibrational levels. Sternberg (1989) has described calculations of the far-ultraviolet spectrum of H_2 , however Hurwitz (1998) find that these models overpredict the observed short-wavelength intensity by roughly an order of magnitude. Such trends are hinted at in the model spectrum of Witt et al. (1989), although it seems that *IUE* did not go deep enough into the far-ultraviolet to see this effect fully.

Given these concerns, we adopt a modified version of the synthetic spectrum presented by Wolven et al. (1997) to model fluorescence induced by solar Ly- α at the Shoemaker-Levy 9 impact site on Jupiter. These models are an improvement over what is described in Sternberg (1989) by including photoexcitation cross-sections computed using the line transition probabilities from Abgrall et al. (1993a,b). The ratio of atomic to molecular hydrogen column densities is fixed to be 0.1, extrapolating the values found in the translucent cloud survey of Rachford et al. (2002). Additionally, the Wolven models allow for absorption out of upper vibrational states ($v \geq 0$), includes transitions to vibrational states that result in dissociation ($v' > 14$, the vibrational continuum), and includes a first-order correction for self-absorption by H_2 at wavelengths less than 1100 Å.

There are several differences between the model described in Wolven et al. (1997) and the one presented here. The first is that we only consider the photo induced fluorescence, no electron-impact induced contribution is included. The solar Ly- α profile that was the excitation spectrum has been replaced by the flux calibrated *FUSE* spectrum of γ Cas, described in the next section and shown in Figure 4. We only include the 917 – 1182 Å region covered, but with the majority of the upper states populated through absorption between the Lyman limit and the (0 - 0) band near 1108 Å, we expect errors induced by this estimation to be minor. The fluorescence code described here uses two temperature components, the rotational temperature quoted in Habart et al. (2004), 620 K, and a higher “non-thermal” temperature of 2500 K that was required to find agreement with the *HUT* data. The feature near 1578 Å that is produced in transitions to the vibrational continuum of the ground electronic state was underpredicted without a high-temperature component. We also use the column density from Habart et al. (2004; $5 \times 10^{21} \text{ cm}^{-2}$) and an additional absorption contribution calculated using the *H2ools* optical depth templates described in McCandliss (2003). While not a perfect fit to the data, we find that this model approximately reproduces the relative line strengths with smaller (factor of ≤ 2) discrepancies in absolute flux between the longest and shortest ultraviolet wavelengths.

Flux Calibrated Far-Ultraviolet Spectrum of γ Cas

γ Cas exceeds the *FUSE* bright target limit by almost two orders of magnitude, but observing the instrumentally scattered spectrum of the star allows the spectral characteristics to be recorded while protecting the primary science detectors. HD 5394 was observed by *FUSE* using this offset technique on 2002 December 16 under the bright-object program (S52107). During this 3.1 ks observation, the LWRS aperture was located $\sim 1'$ from γ Cas ($RA = 00^h 56^m 50.65^s$, $\delta = +60^\circ 42' 53.0''$, J2000). Spectra were obtained on the 2A and 2B detector segments, providing wavelength coverage from 916.6 – 1181.9 Å. A flux calibration was performed using the sounding rocket spectrum of γ Cas described below.

γ Cas was observed by a rocket-borne spectrograph in 2003 December. This was the first flight of the Long-Slit Imaging Dual-Order Spectrograph (LIDOS, McCandliss et al. 2002). LIDOS employs two complementary ultraviolet-sensitive detectors to achieve a large dynamic range in flux for imaging spectroscopy. An updated version of the Faint Object Telescope (0.4-meter diameter, $f/15.7$ Dall-Kirkham; Hartig et al. 1980; McCandliss et al. 1994; France et al. 2004) focuses light at the entrance aperture of the spectrograph, a mirrored slit-jaw into which a long-slit ($10'' \times 300''$) is etched. The light entering the 600 mm diameter Rowland spectrograph is dispersed by a SiC grating. Far-UV light diffracted in the +1 order (900 – 1590 Å) is recorded by a windowless δ -doped CCD that is sensitive to bright objects whereas the -1 order UV light (930 – 1680 Å) is recorded by a photon-counting micro-channel plate (MCP) detector with a CsI photocathode readout by a double delay-line anode. The MCP detector has a low background equivalent flux, extending our detection limit towards fainter diffuse objects.

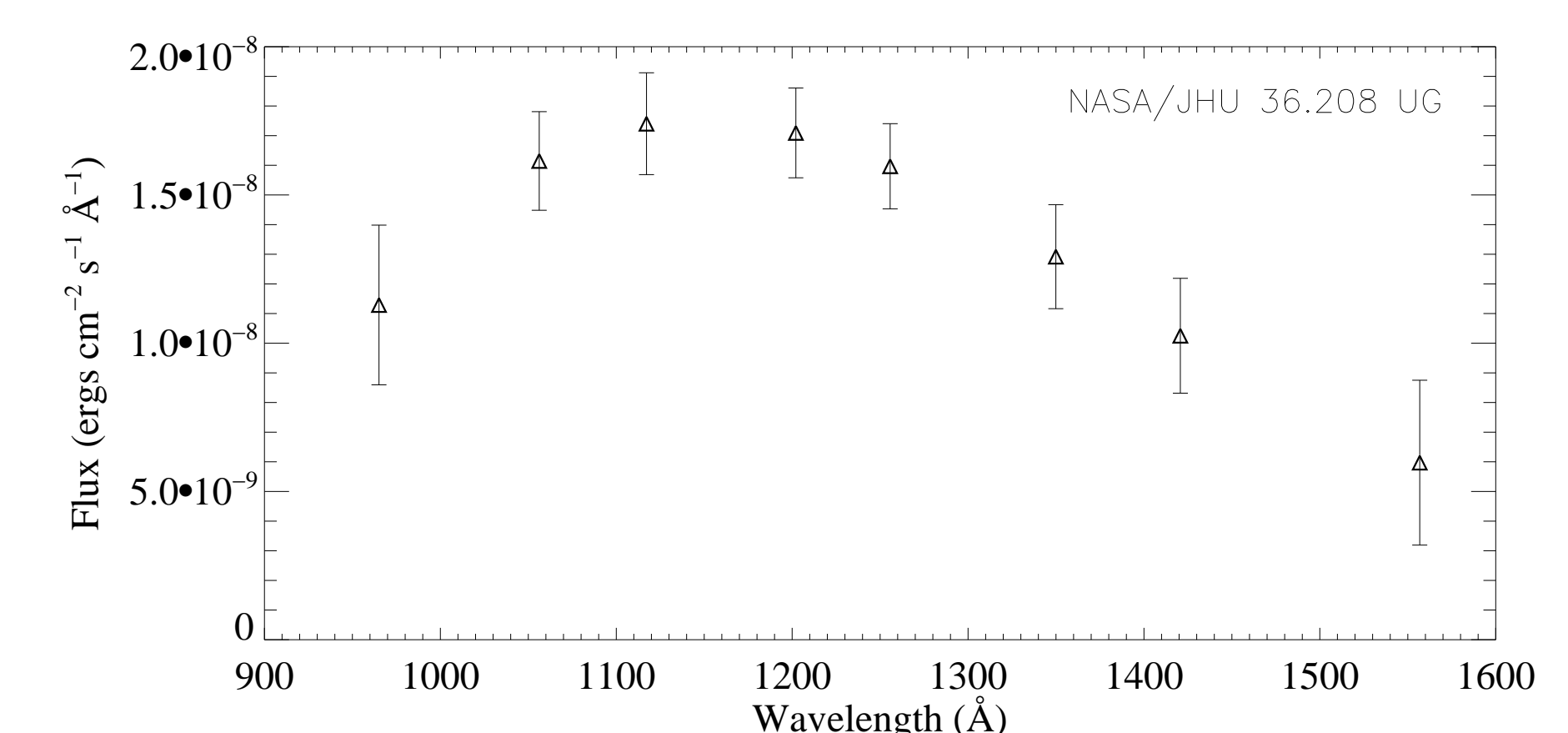


Figure 4. Low resolution rocket-borne CCD spectrum of γ Cas. The absolute calibration of this spectrum was used to transfer calibration to the scattered light spectrum obtained by *FUSE*.

LIDOS was launched aboard a Black Brant IX sounding rocket (NASA 36.208 UG) from White Sands Missile Range, New Mexico ($106^\circ 3$ West, $32^\circ 4$ North), on 2003 December 16 at 20:00 MST. The target was obtained by referencing the startracker to a bright star (Polaris) and our target (γ Cas). The obtained field is within a few arcminutes of the nominal pointing, and this field is relayed to the ground in real-time through a Xybion TV camera imaging the slitjaw ($20'$ field-of-view). Fine adjustments are performed in real-time via commands to the ACS. γ Cas was placed in the spectrograph slit near T+200 seconds and a 28 second exposure was obtained with the CCD, shown in Figure 5. Bias and dark frames were also obtained in-flight. Following the CCD exposure, the MCP high-voltage was turned on and pointing offsets were made to both IC 59 and IC 63. The integration time was sufficiently short on the two nebulae that only a scattered light spectrum of IC 63 was detected.

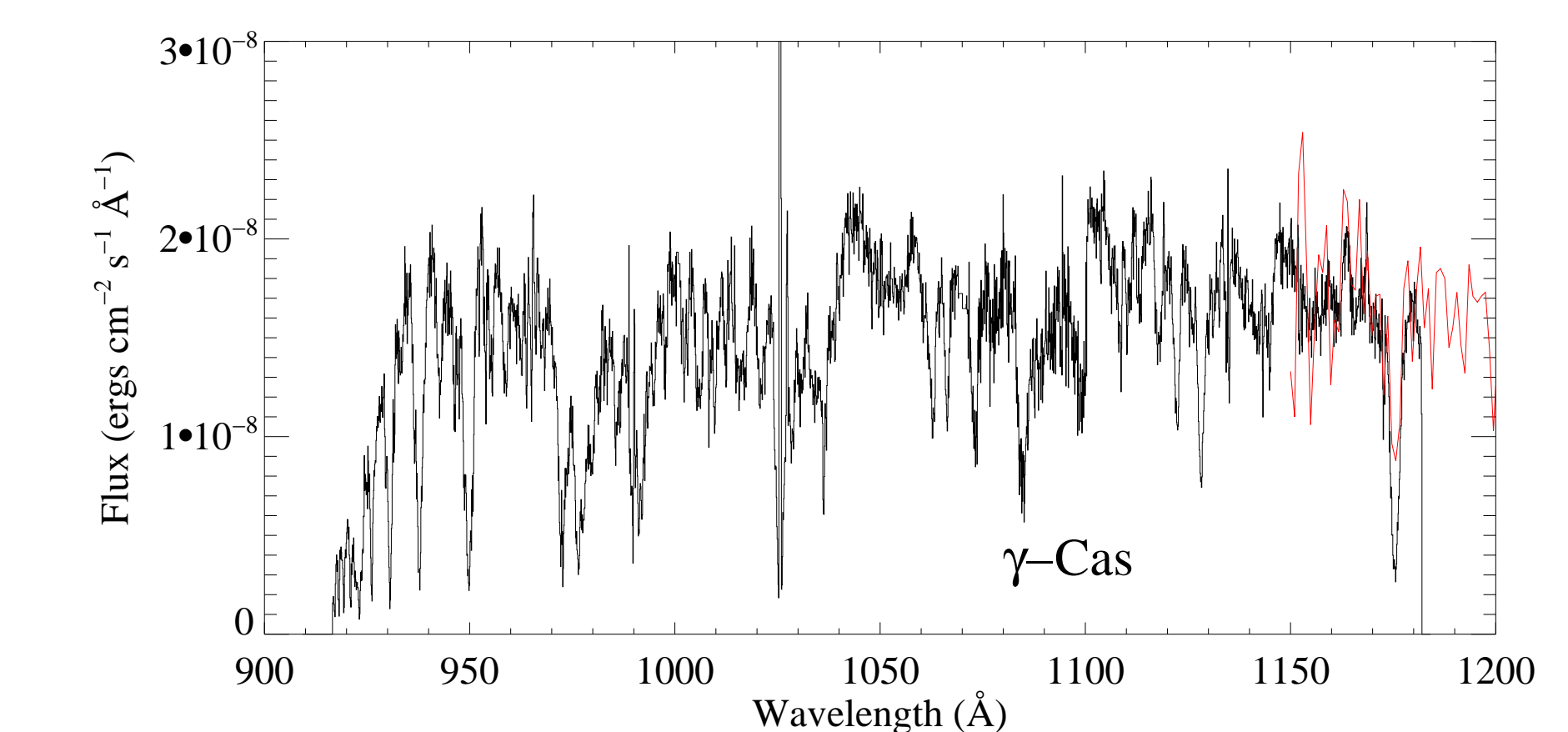


Figure 5. The *FUSE* scattered light γ Cas (HD 5394) was flux calibrated by comparison with the low resolution rocket-borne spectrograph. The *IUE* spectrum of γ Cas is shown in red in the overlap region. The calibrated *FUSE* spectrum was used as the incident radiation field in the fluorescence model.

We wish to thank Eric B. Burgh for helpful discussion and the optical image of IC 63. *FUSE* results were obtained under Guest Investigator program B112 and the bright object project S521 of the NASA-CNES-CSA *FUSE* mission operated by The Johns Hopkins University supported by NASA contract NAS5-32985. *HUT* data were obtained from the MAST archive. The sounding rocket observations of γ Cas were supported by NASA grant NAG5-5122 to The Johns Hopkins University.

Author Contact:

france@pha.jhu.edu
http://www.pha.jhu.edu/~france/

REFERENCES

- Abgrall, H., Roueff, E., Launay, F., Roncin, J. Y., & Subtil, J. L. 1993a, *A&AS*, 101, 273–.
- Abgrall, H., Roueff, E., Launay, F., Roncin, J. Y., & Subtil, J. L. 1993b, *A&AS*, 101, 323–.
- Duley, W. W. & Williams, D. A. 1980, *ApJ*, 242, L179–L182.
- France, K., McCandliss, S. R., Burgh, E. B., & Feldman, P. D. 2004, *ApJ*, 616, 257–265.
- Habart, E., Boulanger, F., Verstraete, L., Walmsley, C. M., & Pineau des Forêts, G. 2004, *A&A*, 414, 531–544.
- Hartig, G. F., Fastie, W. G., & Davidsen, A. F. 1980, *Appl. Opt.*, 19, 729–740.
- Hurwitz, M. 1998, *ApJ*, 500, L67+.
- Jansen, D. J., van Dishoeck, E. F., & Black, J. H. 1994, *A&A*, 282, 605–620.
- Luhman, M. L., Luhman, K. L., Benedict, T., Jaffe, D. T., & Fischer, J. 1997, *ApJL*, 480, L133–L136.
- McCandliss, S. R. 2003, *PASP*, 115, 651–661.
- McCandliss, S. R., France, K., Feldman, P. D., & Pelton, R. 2003, In *Future EUV/UV and Visible Space Astrophysics Missions and Instrumentation*, Edited by J. Chris Blades, Oswald H. W. Siegmund, *Proceedings of the SPIE*, Volume 4854, pp. 385–396.
- McCandliss, S. R., Martinez, M. E., Feldman, P. D., Pelton, R., Keski-Kuha, R. A., & Gum, J. S. 1994, In *Proceedings of the SPIE*, Volume 2011.
- Rachford, B. L., Snow, T. P., Tamplin, J., Shull, J. M., Blair, W. P., Ferlet, R., Friedman, S. D., Gry, C., Jenkins, E. B., Morton, D. C., Savage, B. D., Sonnenstrucker, P., Vidal-Madjar, A., Welty, D. E., & York, D. G. 2002, *ApJ*, 577, 221–244.
- Sternberg, A. 1989, *ApJ*, 347, 863–874.
- Witt, A. N., Stecher, T. P., & Boroson, T. A. and Bohlin, R. C. 1989, *ApJL*, 336, L21–L24.
- Wolven, B. C., Feldman, P. D., Strobel, D. F., & McGrath, M. A. 1997, *ApJ*, 475, 835–.

Fig. 1.—

Fig. 2.—

Fig. 3.—

Fig. 4.—

Fig. 5.—

Fig. 6.—