# Far-Ultraviolet Dust Scattering and Extinction in IC 405

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## Abstract

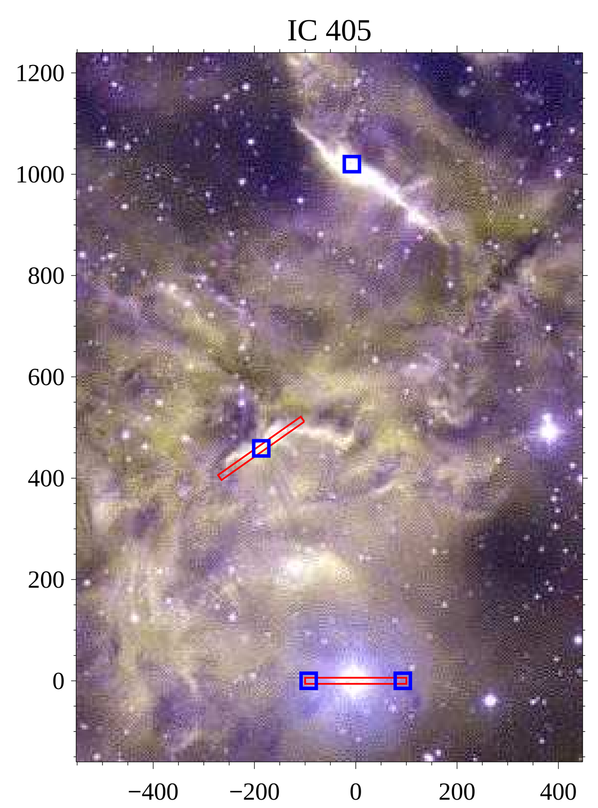
We present results from a NASA/JHU sounding rocket mission (36.198 UG) during which we acquired a longslit ($12'' \times 200''$) spectrum of the reflection nebula IC 405 in the 900 - 1400 Å wavelength region. Several pointings within the nebula were obtained, including a high quality (S/N ≈ 10-15 at $R$ = 300) spectrum of the central star, HD 34078. Observations of the nebula reveal a surface brightness to stellar flux ratio that rises by two orders of magnitude to the blue in our bandpass. This is in contrast with the relatively flat nebular dust scattering observed during a prior sounding rocket observation of the reflection nebula NGC 2023.

Several possibilities have been suggested to explain the blue rise that is exhibited in IC 405. Differential extinction within the nebula, such as a particular clump of dust along the line of sight, is one possibility. Unresolved fluorescent molecular hydrogen emission is another possible explanation. Models of nebular dust scattering, similar to those of Burgh et al. 2002, have been compared to the data and results will be discussed. We will explore the possibility of differential extinction with an observing program to measure Balmer line ratios within the nebula with the Dual Imaging Spectrograph at Apache Point Observatory. Additionally, IC 405 has been observed as a Cycle 4 target of the Far Ultraviolet Spectroscopic Explorer, and preliminary results are presented.

## Sounding Rocket Observations of IC405

IC 405 is a reflection nebula in Auriga, shown below with the relevant aperture overlays. It is illuminated by a central star, AE Aur (HD 34078), a runaway from the Orion Nebula moving with a large proper motion through the nebula (≈ 17 AU/yr). AE Aur is thought to be cospatial with the nebula at a distance of about 450 pc. It is bright in both the visible (V = 6.0) and the ultraviolet (HD 34078 – O9.5 Ve), although it is rather extincted ($E(B-V) = 0.53$).

One method of determining the physical properties of gas and dust in the interstellar medium (ISM) is to study their interaction with stars. Reflection nebulae offer an opportunity to study dust absorption and scattering properties, excitations of the atomic and molecular gas species present, and how they alter the intrinsic stellar spectrum. One measurement that can shed considerable light on the processes occurring in the nebula is the ratio of its surface brightness to the stellar flux ($S/F_\star$). In principle, this requires two measurements, a spectrum of the exciting star(s) and a separate spectrum of the nebular region. This measurement was made in a single observation through the use of a rocket-borne imaging spectrograph. A telescope focuses the target at the entrance aperture of the instrument, an evacuated Rowland Circle spectrograph, using a microchannel plate stack detector with a KBr photocathode, readout by a double delay-line anode. The spectrograph achieves a pointing limited spectral resolution of ≈ 3 Å . This experiment was launched aboard a Mark 70 Terrier-Black Brant IX sounding rocket from White Sands Missile Range. Figure 2 illustrates the long-slit spectrum of the star and nebula measured during the flight.




The stellar spectrum obtained during the flight, shown in Figure 3, is consistent with previous FUV measurements. Following the extraction of both the stellar and nebular spectra, the $S/F_\star$ ratio can be measured, and it is this ratio that displays the rise of roughly two orders of magnitude to the blue from 1400 to 900 Å . The case for this "blueness" is strong for the nebular regions near the central star and a similar trend appears in the nebular offset pointing. Figure 1 shows the $S/F_\star$ ratios. This result is in rather stark contrast to previous observations of a flat $S/F_\star$ in other reflection nebulae. An identical measurement has been made for NGC 2023, using the same instrument and experimental configuration and an analogous observation was made of NGC 7023, using a combination of data from Voyager 2 and the Hopkins Ultraviolet Telescope (HUT), aboard Astro-1.

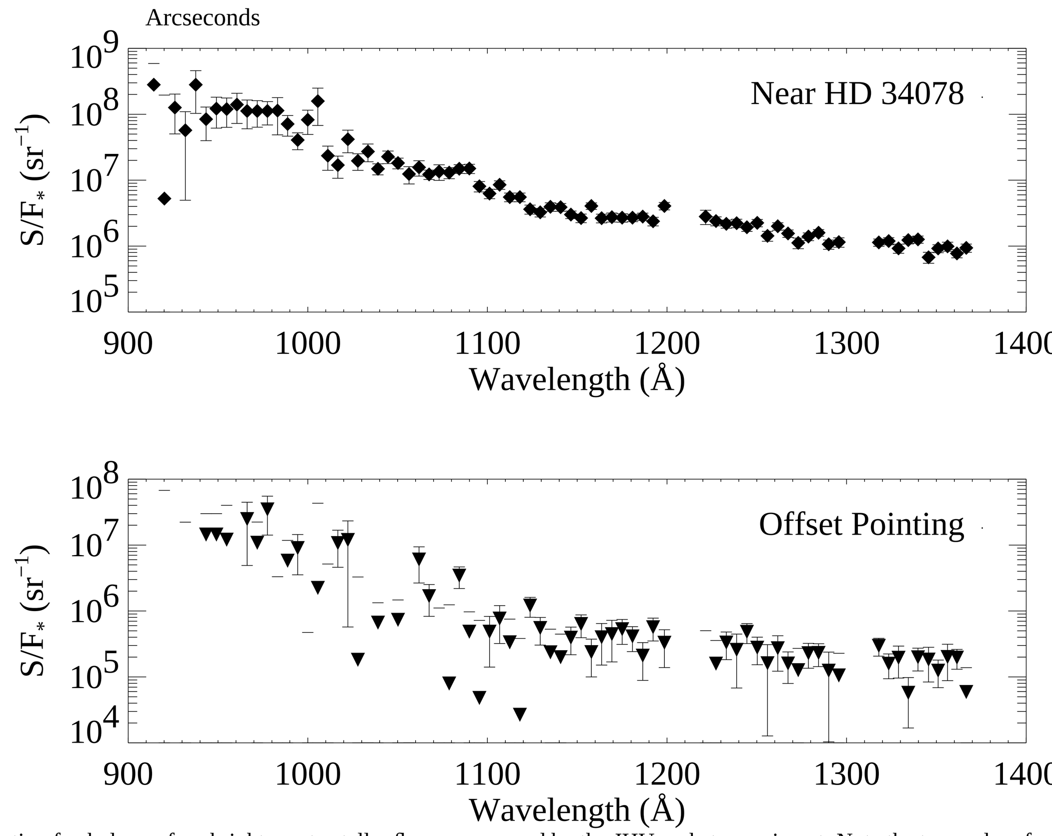



Figure 1. The ratio of the nebular surface brightness to stellar flux as measured by the JHU rocket experiment. Note the two order of magnitude rise to the blue across the bandpass of the instrument. At wavelengths shorter than 1150 Å, the on-star pointing displays a rough $\log_{10}(S/F_\star) \approx \lambda^{-1}$ dependence.

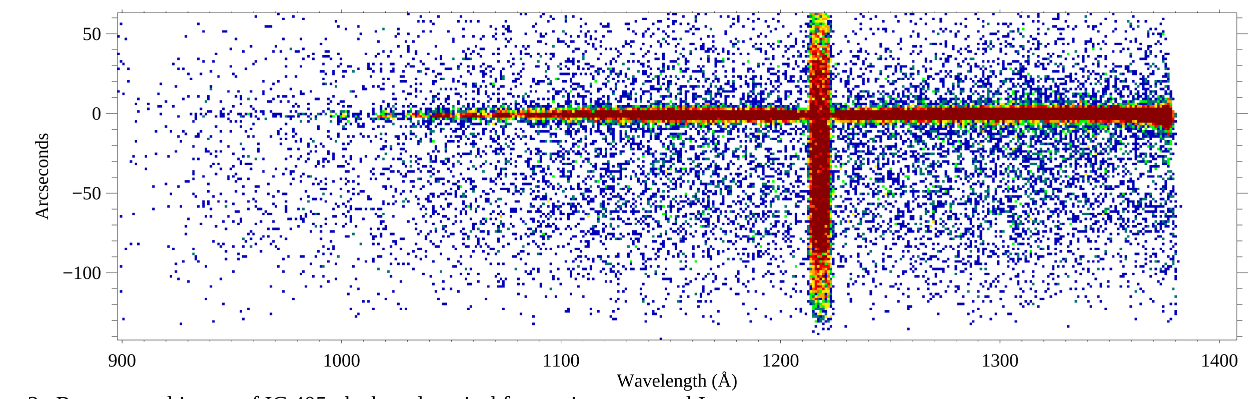



Figure 2. Raw spectral image of IC 405, the broad vertical feature is geocoronal Lyman-α.

Burgh et al. have modeled the dust scattering in NGC 2023 and determine that the observed spectrum is due to a decreasing albedo, $a$ balanced by an increasing phase function asymmetry parameter $g$ ($\equiv \langle \cos \theta \rangle$), implying an improved absorption efficiency balanced by more strongly forward scattering grains. Murthy et al. explain the flat spectrum in NGC 7023 by having a decreasing albedo balanced by an increase in the flux of fluorescent molecular hydrogen ($H_2$) across the bandpass. There are a number of possible explanations for the IC 405 result, such as nearby, lightly extincted stars contributing to the nebular scattered light. Differential extinction within the nebula, i.e., a particular clump of dust along the line of sight, could explain the result. Dust scattering models similar to those of Burgh et al. have been compared to the data and suggest unrealistic values for $a$ and $g$ for the simple geometries modeled (see below). In particular, albedos that approach unity, suggesting an emission process. Some sort of "extended blue emission" from dust is only speculative, and emission from nebular gas is the more traditional explanation. $H_2$ fluorescence in IC 405 was detected by HUT (unpublished), and as the majority of the UV emission lines of $H_2$ fall within our bandpass, we propose this as another possible explanation.

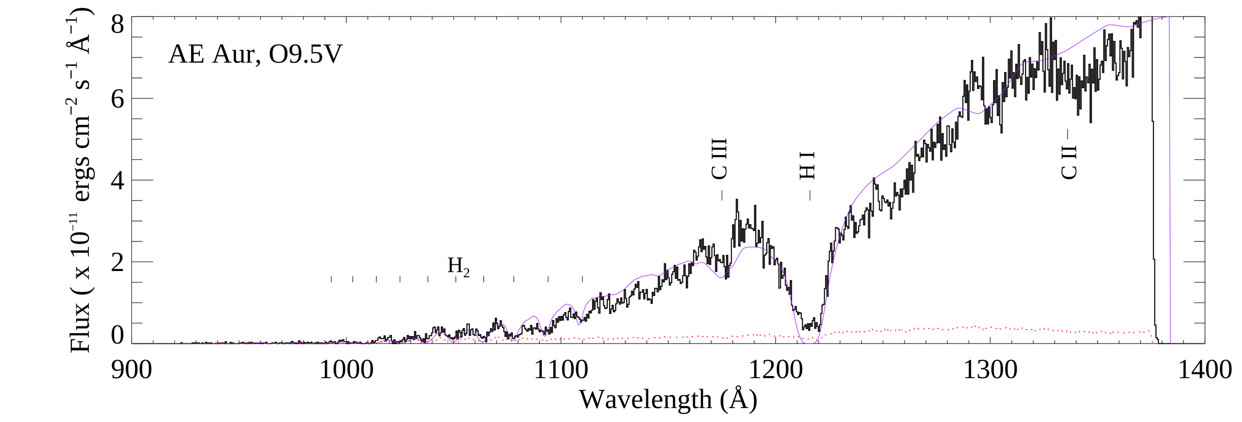



Figure 3. The spectrum of HD 34078, overplotted with a Kurucz stellar model extincted by the parametrization of Fitzpatrick and Massa (1990).

## Dust Scattering Models

The dust scattering in IC 405 was modeled using a modified version of the code described by Burgh et al. (2002), employing a Monte Carlo dust radiative transfer model (see also Gordon et al., 2001). The model follows the path (direction and position) of each photon in the nebula from its "creation" at the position of the star, until it leaves the nebula (i.e, its radial position is outside the defined size of the nebula). The factors that determine the position and direction of the photons during their propagation through the nebula are the optical depth of the dust, the fraction of photons scattered by the dust versus absorbed (the albedo), the angular distribution for the scattered photons (parameterized by $g$), and the geometry of the dust distribution. The scattering distribution is given by the Henyey-Greenstein phase function, although Draine (2003) has argued that the H-G function is inappropriate in the FUV bandpass. A revision of our model replacing the H-G phase function with a function that depends on the scattering cross-sections for dust grains in the FUV (as well as more sophisticated geometries) is underway. Given inputs for the number of photons followed, the optical depth, albedo, and $g$, the model outputs an image of nebular surface brightness that can be compared to the distribution measured by the rocket experiment. The rocket data are binned by wavelength region to improve S/N, and then plotted as a function of spatial position along the slit.

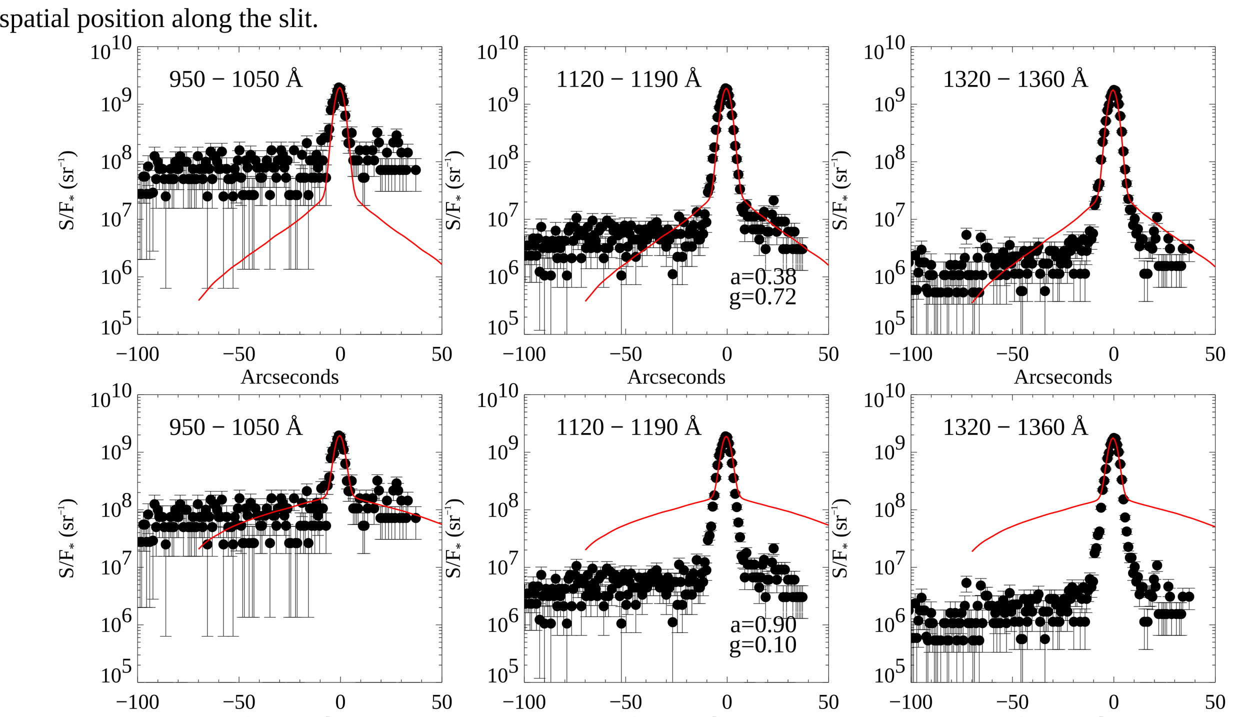



Figure 4. Spatial $S/F_\star$ measured with the rocket experiment compared with models. The top panels are models using theoretical values of $a$ and $g$ at 1350 Å, the bottom panels attempt to fit the short wavelength $S/F_\star$, using a differential extinction of 50 % with $a$=0.9 and $g$=0.1. The models differ from the one described in Burgh et al. by the use of a geometry that employs a larger inner cavity cleared out by the stellar wind and high proper motion.

Figure 4 shows how this model, which closely approximates the observed surface brightness distribution in NGC 2023, fails to reproduce the nebular surface brightness of IC 405 by orders of magnitude. The top model shows the results using the $a$ and $g$ from Weingartner and Draine (2001) for $R_V$ = 4.0. The model shows poor agreement across the bandpass, particularly at the short wavelength end (a result of the nebular "blueness"). The second model, in the bottom three panels, shows the best fit to the short wavelength data, revealing $a$ = 0.9, $g$ = 0.1, in strong disagreement with both theoretical and other measured values in this wavelength regime. Additionally, a 50 % differential extinction was applied the best-fit 950-1050 Å model, the stellar flux directly along the line of sight to the observer was reduced by a factor of two. As this model begins to reproduce the short wavelength result, it is clearly inappropriate at longer wavelengths.

## First Results from FUSE

Figure 5 shows nebular spectra of IC 405 recently obtained by FUSE. The two pointings shown are from a region near the star that corresponds to the "on-star" rocket position (Position 1) and a region ≈ $1000''$ to the north of the star (Position 4), a filament exhibiting Extended Red Emission (unpublished). Position 1 shows the scattered stellar continuum, yet little evidence for emission from fluorescent $H_2$ while further away from the star where the contribution from scattered light is reduced by about an order of magnitude, the fluorescent emission is clearly detected. The intermediate pointing, Position 3, displays a mix of scattered light and hydrogen emission (not shown). Below are the nebular surface brightness to stellar flux ratios for the 3 positions so far observed by FUSE. A power law was fit to the data at points that were not contaminated by airglow or strong scattered $H_2$ absorption troughs, and a $\log_{10}(S/F_\star) \approx \lambda^{-1}$ relation holds throughout the nebula, consistent with the rocket result. (We restricted the fit to $\lambda \leq 1150$ Å to avoid "The Worm" in the stellar spectrum) The fact that the $S/F_\star$ ratio is strongly blue even where little or no $H_2$ emission is detected seems to rule out a population of fluorescing molecular hydrogen as the cause for the "blueness" of IC 405. This result suggests that differential extinction between the stellar line of sight and the nebular sightlines is responsible for the blue rise.

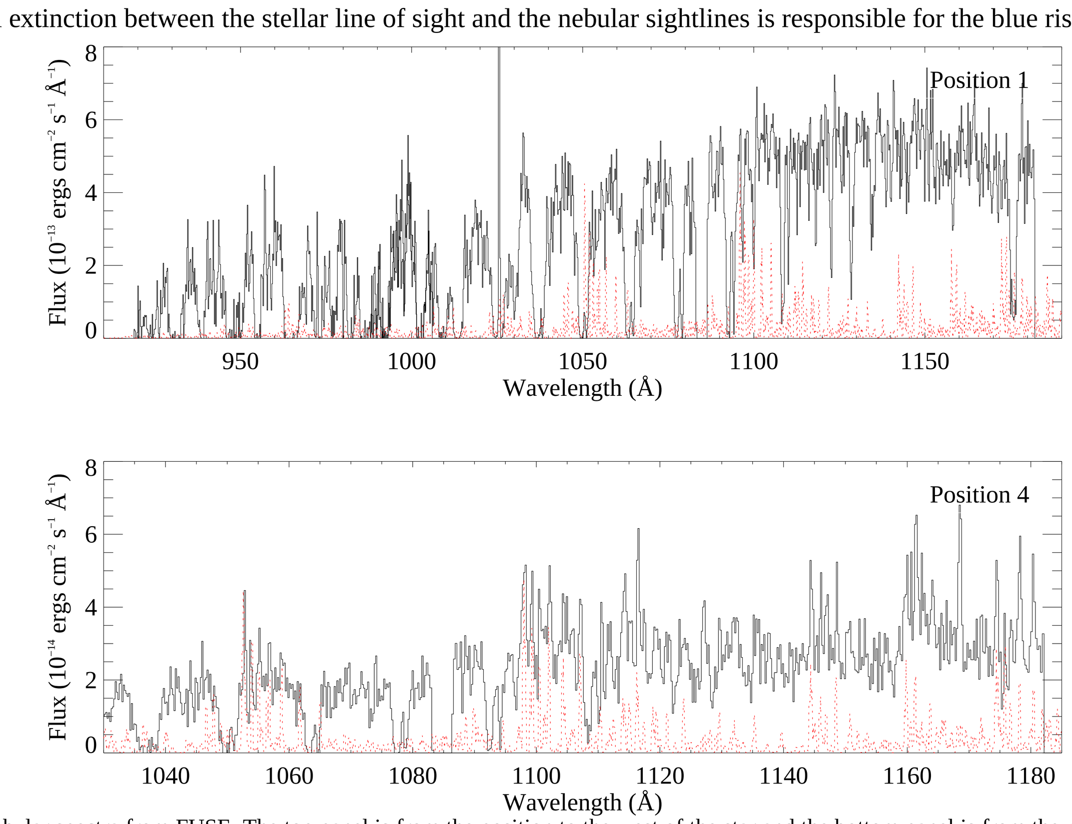



Figure 5. Nebular spectra from FUSE. The top panel is from the position to the west of the star and the bottom panel is from the northern most pointing. The more distant pointing shows a more pronounced signature of fluorescent $H_2$. Overplotted in red is a synthetic spectrum of $H_2$ emission (see Wolven et al., 1997) to guide the eye.

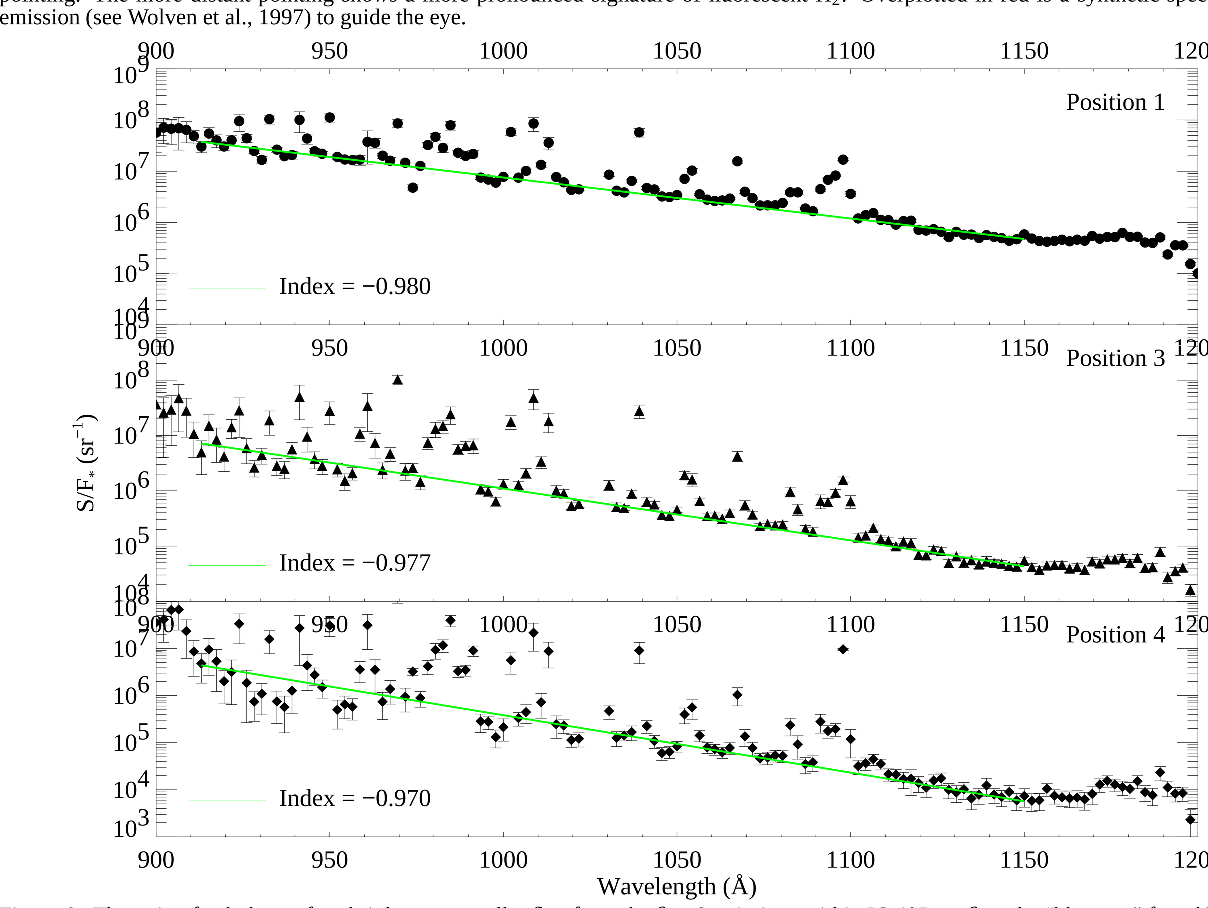



Figure 6. The ratio of nebular surface brightness to stellar flux from the first 3 pointings within IC 405 confirm the "blueness" found by the JHU rocket experiment. The FUSE spectrum of HD 34078 was retrieved from the MAST archive.

## Conclusions

We have presented results of far-ultraviolet spectroscopy of the reflection nebula IC 405. The surprising rise in $S/F_\star$ by two orders of magnitude to the blue was observed during rocket observations. The possibility of the nebular surface brightness being caused by the fluorescent emission from molecular hydrogen was explored with FUSE observations of several regions within the nebula. The FUSE spectra show that scattered stellar light dominates near AE Aur and that molecular hydrogen emission is more pronounced further away from the star, but that the $S/F_\star$ ratio is insensitive to the relative contribution of $H_2$. We conclude that differential extinction along different lines of sight within the nebula is the cause of the "blueness" of IC 405.

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