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Fluorescent Molecular Hydrogen in IC 63

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Abstract.
We present *FUSE* observations of fluorescent molecular hydrogen in IC 63, an emission/reflection nebula illuminated by γ-Cas, a B0IV star 1.3 pc from the head of the bright optical nebula. IC 63 was the first reflection nebula in which molecular hydrogen emission was detected in both the mid-UV (*IUE*-SWP band) and far-UV (*FUSE*, *ORFEUS* bands). We present nebular spectra of three positions in IC 63, obtained in the MDRS aperture in 2001 September. Molecular hydrogen is detected at all three locations, but the line strengths and scattered light contributions are seen to vary with position. We use this data to test models of the fluorescent excitation and emission process. These models have historically overrpredicted the absolute flux of the far-UV emission from IC 63.

1. Introduction

Ultraviolet fluorescent emission is second step in the process that gives rise to the well studied near-infrared emission spectrum of molecular hydrogen. 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 & 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 contiuum source. In 1990, IC 63 was observed across the entire 912 – 1800 Å band spanned by the electronic transitions ($B^1\Sigma_u^+ - X^1\Sigma_g^+$ and $C^1\Pi_u - X^1\Sigma_g^+$) that give rise to the ultraviolet emission spectrum by *HUT*, see Figure 1. 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 proceeding, 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 Ly-α (France et al. 2004).

2. Far Ultraviolet Spectra

2.1. *HUT* Observation

HUT observations of IC 63 show the fluorescence spectrum across the ultraviolet emission band of H_2. A scattered light subtraction has been made following the procedure of Witt et al. (1989). The scattered light was assumed to have a form $aF_\star\lambda^\beta$ where $F_\star$ was made from a composite of archival *IUE* and *FUSE* spectra. We find that $a = 1.3 \times 10^{-5}$ and $\beta = 1.5$. Models of H_2 fluorescence are overplotted, the normalization is based on the requirement that the models match the data at the 1608 Å peak. We confirm the short-wavelength discreperancy seen by Witt et al. (1989) and Hurwitz (1998).

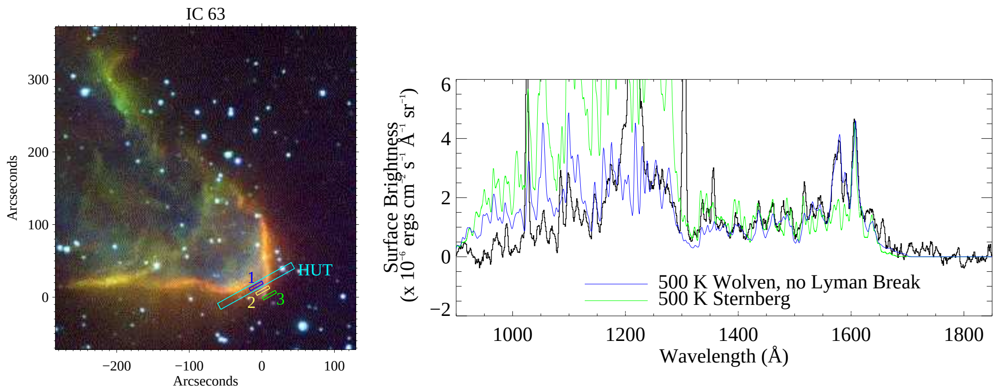

Figure 1. Left: IC 63 with relevant aperture overlays. γ-Cas is located approximately 20′ to the southwest. Image courtesy of Eric B. Burgh. Right: The *HUT* spectrum of IC 63 overlaid with models of H_2 emission.

2.2. *FUSE* Observations

IC 63 was observed by *FUSE* on 09 and 10 September 2001. The (4”×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 tenative detection at POS3. The strongest molecular hydrogen line complexes are centered on 1055, 1100, 1115, and 1161 Å. C II* λ1037 and N II* λ1085 are seen strongly at all three positions. S III* λ1021 is seen seen clearly at POS1 and POS3 and N II λ916 is seen weekly in the SiC 1B channel. Interestingly, we do not detect the ground state transitions of any of the ions listed above. C II λ1036, for example, would be expected to be roughly half as strong as the excited C II* line, detectable at the S/N of our observations. We attribute this behavior to self-absorption by ground state ions within the nebula. This is supported by the off-nebula spectra simultaneously acquired in the LWRS (30”×30”) aperture. While C II λ1036 is still undetected, the lower lying transitions of N II (λ1084) and S III (λ1012 and λ1015) are seen. This suggests that the ionized nebula extends beyond both the bright optical emission and the molecular emission, traced by the H_2 fluorescence and the CO maps of Jansen et al. (1994).

3. Fluorescent Molecular Hydrogen Model

Synthetic spectra of fluorescent emission from molecular hydrogen can be made by assuming 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 an excited rovibrational level. 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

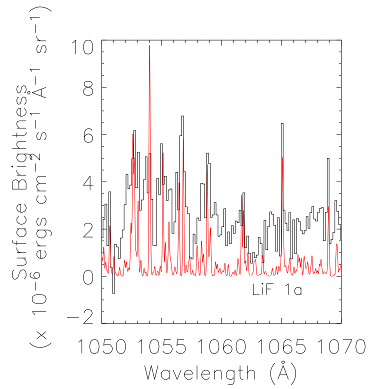

Figure 2. Two bands of fluorescent molecular hydrogen emission seen in IC 63. These observations have permitted us to refine models of H_2 fluorescnce, shown in red. Traditionally, models have overpredicted the observed far-UV flux by as much as an order of magnitude (Hurwitz 1998).

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 (1993a,b) . Additionally, the Wolven models allow for absorption out of upper vibrational states ($\nu \geq 0$), includes transitions to vibrational states that result in dissociation ($\nu'' > 14$, the vibrational continuum), and includes a first-order correction for self-absorption by H_2 at wavelengths less than 1100 Å. There are two primary differences between the models described in Wolven et al. (1997) and those presented here. The first is that the we only consider the photon induced fluorescence, no electron-impact induced contribution is included. Second, the solar Ly-α profile has been replaced by a synthetic B0 V stellar spectrum generated by SynSpec. While not a perfect fit to the data, we find that this model approximately reproduces the relative line strengths with smaller (factor of ~ 2) discreperancies in absolute flux between the longest and shortest ultraviolet wavelengths.

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