Fluorescent Molecular Hydrogen in Reflection Nebulae
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Abstract

Molecular hydrogen plays an important role in many astrophysical environments, among which are photodissociation regions. A photodissociation region is a gas rich interstellar region, usually in close proximity to a hot central object such as a massive star or stellar remnant. Such a region has a strong ultraviolet continuum radiation field, an environment favorable for a variety of atomic and molecular excitation and emission mechanisms. Of particular interest is fluorescent emission of molecular hydrogen, in which a hydrogen molecule absorbs an ultraviolet continuum photon and is excited into a higher electronic and vibrational state. The resulting fluorescence produces a rich ultraviolet and infrared spectrum that we can observe using a combination of ground and space-based instruments. This process redistributes the energy from the illuminating source and introduces byproducts that can influence additional processes in these regions. I propose to study this fluorescent emission process, using existing and future observations, in order to better constrain models of energy transport and distribution in photodissociation regions.

1 Introduction

Molecular hydrogen is the most abundant molecule in the universe and is important to many processes in astrophysics. It plays a role in situations as diverse as structure formation in the early universe (Lepp and Stancil 1998), dense star forming regions (Shull and Beckwith 1982), and photodissociation regions (Martini, Sellgren, and DePoy 1999; Hollenbach and Tielens 1997). Molecular hydrogen (H_2) is important as a coolant in astrophysical environments. The lowest energy electronic transition to the ground state of atomic hydrogen corresponds to a temperature of order 10^5 K (hence there is no mechanism to allow the gas to shed energy and lower its temperature much below this value), whereas the lowest rotational transitions of H_2 correspond to temperatures of only a few hundred degrees. This efficiency as a coolant allows gas to release internal energy when collapsing to form galaxies (in the early universe) and stars (present day).

Photodissociation regions (PDRs) are ideal places to observe H_2 playing an important role in the transport and redistribution of energy. Generally, a PDR is a region of predominately neutral gas and dust (with a fraction of the gas in molecular form), such as the interface between a region of ionized atomic gas and cooler, molecular gas. PDRs are generally bathed in an intense radiation field which interacts with the gas and dust that act to transport the energy away from the source. Under such conditions, molecular hydrogen can absorb the ultraviolet radiation from the nearby source, redistributing the energy throughout the electromagnetic spectrum via the fluorescent emission process or changing the composition of the region through its dissociation products. I propose to characterize the role H_2 plays in a subclass of PDRs, using existing and future observations, in order to better constrain models of the distribution and transport of energy in these regions.

2 Physical Background

H_2 is a homonuclear molecule, and as such, it has no intrinsic dipole moment, as one finds in a molecule such as carbon monoxide. This lack of dipole moment means that it radiates primarily through the slower channels of quadrupole transitions. H_2 can be excited (or *pumped*) into higher electronic and vibrational states by the absorption of a far-ultraviolet (FUV) photon ($912 < \lambda < 1108$ Å) coming either from the UV radiation field of a star or the less intense average interstellar radiation field. The absorption of such a photon predominately causes an electronic excitation to a higher bound state ($B^1\Sigma_u^+$ or $C^1\Pi_u$), during which the molecule can also be excited into a higher vibrational level of the excited electronic state, see Figure 1. The molecule then emits to a discrete vibrational level of the ground electronic state ($X^1\Sigma_g^+$), producing a fluorescent spectrum in the UV from 912 – 1650 Å (Sternberg 1989). The molecule can then cascade back to the ground vibrational state via the quadrupole transitions mentioned above, producing a fluorescent spectrum in the near-infrared (NIR) (Martini, Sellgren, and DePoy 1999). Approximately 10 - 15% of the time, this fluorescent pumping process will leave the molecule in the vibrational continuum of the ground electronic state, resulting in its dissociation (Shull and Beckwith 1982). This fluorescent process can be important in determining the transport of energy for a number of reasons. It redistributes the flux from the exciting object from a narrow window in the FUV (which roughly corresponds to the peak of the blackbody curve for OB-type stars) to other regions of the electromagnetic spectrum. In the UV, dust tends to be strongly foward scattering with a decreasing albedo (Burgh, McCandliss, and Feldman 2002) so fluorescent emission can appear to offset the extinction effects of dust (Witt et al. 1993; Fitzpatrick and Massa 1990).

H_2 can affect its own population through fluorescent pumping. Pumping leads to a fractional molecular dissociation, however the formation of H_2 on grains is directly proportional to the amount of atomic hydrogen (H I) present (Cazaux and Tielens 2002; Shull and Beckwith 1982), hence the dissociation that leads to the *destruction* of molecular hydrogen also aids in its *creation*. Additionally, the byproducts of the fluorescent process, H I and vibrationally excited H_2, play important roles in determining the chemistry of PDRs (Hollenbach and Tielens 1997). Finally, grain surface composition could be altered due to accretion of the modified chemical products (Whittet 1984). The properties of the dust itself (such as its albedo and the degree of its forward scattering) can be affected by changes in surface composition. Changing the properties of grains can effect the overall extinction due to dust in these regions. Clearly, fluorescent pumping of molecular hydrogen can have numerous and intertwined consequences.

There are complications in the clear detection of the fluorescent process as H_2 can be excited into low-lying vibrational levels of the ground electronic state by collisions in warm gas when the density is above a critical value ($\approx 10^4$ cm^{-3}). Such thermal effects can be due to the proximity of the exciting source (hence the strength of the radiation field) and shocks, thus strong near-infrared emission of low-lying vibrational levels *is not* conclusive evidence for the fluorescent process described above. Molecular hydrogen will be dissociated in a gas with enough thermal energy to produce electronic transitions (Shull and Beckwith 1982), so detection of the FUV spectrum of H_2 *is* a clear indication of fluorescent pumping. Other clues about the origin of the vibrational excitation of H_2 can come from a closer look at the near-infrared spectrum. Shocked gas in these regions is typically of order a few thousand degrees, and only the first few vibrational levels of the ground electronic state can be substantially populated. Hence, fluorescently pumped gas will have an enhanced population of higher-lying vibrational levels compared to a thermally populated gas (Takami et al. 2000). A ratio of transitions between high-lying levels to transitions of low-lying levels provides a diagnostic that can be used regardless of the absolute H_2 population. It must be noted that both thermal and fluorescently excited populations may coexist in a given spatial region, so one expects variations on the values of these line ratios from object to object (Takami et al. 2000).

3 Targets and Observational Goals

As a subclass of PDRs, nearby reflection nebulae offer an opportunity to study molecular gas. In order to unambiguously detect the fluorescent processes described above, one desires observations of these regions in both the FUV and NIR spectral regimes. Over the past 15 years, several groups have recorded the NIR spectra of the local reflection nebulae, NGC 2023 and 7023 (Martini, Sellgren, and DePoy 1999; Takami et al. 2000). These spectra have shown emission from molecular hydrogen in several excited vibrational levels of the ground electronic state. Additionally, NGC 2023 was recently the target of a rocket-borne imaging spectrograph working in the FUV bandpass, and showed evidence of emission above the modeled scattered light profiles (Burgh, McCandliss, and Feldman 2002). However, the low resolution of the rocket experiment did not allow the discrete emission lines of H_2 to be clearly resolved. The nebula IC 63 was recently observed at high resolution by the Far Ultraviolet Spectroscopic Explorer (FUSE) and confirmed a strong H_2 emission spectrum (Sternberg 1989; Hurwitz 1998; Andersson et al. 2002). The nebula IC 405 was also recently observed by a rocket-borne imaging spectrograph and shows hints of unresolved molecular hydrogen emission above the scattered light as well as a steeply rising ratio of nebular surface brightness to stellar flux across the bandpass of the instrument (900 – 1400 Å), shown in Figure 2. The ratio of the nebular surface brightness to stellar flux can bring out contrasts between scattering and other processes occuring in the nebula; and is independent of an absolute calibration. This behavior has not been observed in other reflection nebulae and one possible explanation is a population of fluorescing molecular hydrogen (France et al. 2002).

I propose to obtain complimentary observations of objects such as these in order to obtain a more complete picture of the physical processes governing PDRs. For these purposes, complimentary observations include the ones described above and future observations of their FUV spectra at high resolution, NIR spectra, and future imaging spectroscopic opportunities from sounding rocket experiments. FUV spectra, obtainable with FUSE, are essential for observing the electronic transitions of H_2, while the NIR spectra, obtainable using IR spectrographs on medium-sized, ground-based telescopes, are needed to look for vibrational transitions. Once found, ratios of the NIR emission lines can reveal information as mentioned above. Future rocket-borne imaging spectrograph observations will allow for additional targets, explore unique abilities to study the star and the nebula simultaneously, and provide a testbed for the development of the next generation of space-borne ultraviolet instrumentation.

3.1 NGC 2023

NGC 2023 is a reflection nebula in Orion, one of the brightest in the sky (Burgh, McCandliss, and Feldman 2002; Martini, Sellgren, and DePoy 1999). It is illuminated by HD 37903, a B1.5V star which is embedded within the nebula (HD 37903, V = 7.84, d $\approx$ 450 pc). NGC 2023 was one of the first objects in which H_2 was detected in the infrared, and several groups have high-quality data sets of these emissions, using both spectroscopy and narrow band imaging (Martini, Sellgren, and DePoy 1999; Takami et al. 2000). As discussed above, NGC 2023 was also observed by a rocket-borne long-slit, imaging spectrograph at low resolution ($R \approx 300$) in the FUV and these data showed evidence for emission above the scattered light models used to characterize the nebula (Burgh, McCandliss, and Feldman 2002). The combination of the FUV and NIR data sets was the basis for an accepted FUSE proposal to obtain high resolution spectra for a variety of pointings within the nebula (McCandliss 2002). These observations are scheduled to be carried out during the current FUSE observing cycle.

3.2 NGC 7023

NGC 7023 is located in Cepheus, at a distance of approximately 440 pc. The central star is HD 200775, a pre-main-sequence B3*e* (V = 7.42). As with NGC 2023, high quality infrared data sets exist, including images and spectra (Martini, Sellgren, and DePoy 1999; Takami et al. 2000). Witt et al., using a combination of spectra from the Hopkins Ultraviolet Telescope (HUT), aboard Astro-1, and data from Voyager 2 explain the roughly constant ratio of nebular surface brightness to stellar flux in the region from 1000 – 1300 Å as the result of fluorescent H_2 emission offsetting a decreasing dust albedo (Witt et al. 1993). Further observations of NGC 7023 with HUT (Astro-2) reveal the strong double peaked emission feature near 1600 Å characteristic of fluorescent molecular hydrogen (unpublished), see Figure 3.

3.3 IC 63

IC 63 is a dense cloud illuminated from the side (in projection) by γ Cas, a B0IV star 1.3 pc from the cloud (HD 5394, V = 2.39, d $\approx$ 190 pc). FUV emission from fluorescent molecular hydrogen was first predicted by Sternberg and discovered by Witt et al. in 1989 with the International Ultraviolet Explorer (IUE), and more recently observed at higher spectral resolution by the ORFEUS telescope and FUSE (Sternberg 1989; Witt et al. 1989; Hurwitz 1998; Andersson et al. 2002). IC 63 became the first object observed to exhibit H_2 fluorescence in both the FUV and the NIR when Luhman et al. discovered several NIR emission lines in 1997 (Luhman et al. 1997).

3.4 IC 405

IC 405 is a reflection nebula in Auriga. The exciting star is AE Aur (O9.5V), a high proper motion runaway from the Orion Nebula, thus not born in the cloud through which it is now passing (HD 34078, V = 6.0, d $\approx$ 450 pc) (Bagnuolo et al. 2001; France et al. 2002). IC 405 was recently observed by a rocket-borne long-slit, imaging spectrograph at FUV wavelengths. Spectra taken near the star show several features that appear to be coincident with known FUV H_2 features, however the resolution of the sounding rocket experiment (again, $R \approx 300$) is insufficient to make a concrete detection. Observations of HD 34078 with FUSE show H_2 in absorption and allowed column densities to be derived for the first 19 ro-vibrational levels, so the coincidences in the rocket data are promising (Le Petite et al. 2001). Additionally, a HUT observation of IC 405 shows the characteristic double peaked feature near 1600 Å mentioned above (unpublished). A long-slit spectrograph obtains data of the star and the surrounding nebulosity simultaneously, and analysis has shown that the integrated nebular surface brightness to stellar flux ratio rises by approximately two orders of magnitude to the blue over the bandpass of the rocket experiment. This dramatic rise to shorter wavelenghts is not observed in either NGC 2023 or 7023, and a population of fluorescent H_2 may be contributing to this discreperancy.

4 Proposed Observations

As mentioned above, high spectral resolution is necessary for unambiguously detecting fluorescent emission from molecular hydrogen in these objects. FUSE, with a resolving power of $\approx$ 3,000 for filled aperture spectra is an ideal instrument with which to observe these emissions. FUSE's wavelength coverage (905 – 1187 Å) does not encompass the entire range of UV emission from H_2, but roughly 70% of the emission falls in its bandpass (Sternberg 1989). This, combined with high sensitivity make high quality FUV spectra obtainable with FUSE. I plan on proposing for FUSE observations of several nebular pointings within NGC 7023 and IC 405 in Cycle 4 (fall 2002). The wealth of supporting data make these observations feasible and attractive. Also, since FUSE spectra of the exciting stars of the nebulae discussed above exist (except γ Cas, which exceeds FUSE's brightness limit), the nebular surface brightness to stellar flux ratios discussed above in the cases of NGC 2023, NGC 7023, and IC 405 can be determined with more certainty, using higher signal-to-noise FUV data sets. Regarding γ Cas, it is scheduled to be a target of a spectrograph currently under development by the Johns Hopkins University Sounding Rocket Group, which will utilize advancements in detector technology in order to obtain the long-slit FUV spectra of γ Cas and IC 63 in the same observation (McCandliss et al. 2002). Figure 4 shows a synthetic molecular hydrogen emission spectrum, as it may be observed with the JHU spectrograph.

These FUV spectra will be used in conjunction with the infrared observations described above. IC 405 has not been obseved in the NIR, to the best of my knowledge, and in order to complete the observations that will allow for an equivalent analysis of these objects, I propose to obtain NIR spectra of IC 405. I plan to propose for time on the near-infrared GRIsm spectrometer and IMager (GRIM II) at Apache Point Observatory (APO) during either the fall 2002 or winter 2003 call for proposals (IC 405 is unavailble during the spring and summer). I will be trained on the APO 3.5-meter telescope by Dr. Stephan McCandliss, who is a certified APO observer (McCandliss 2002).

5 Summary

Molecular hydrogen is the most abundant molecule in the universe, and plays many important roles in astrophysical environments. Photodissociation regions are characterized by a strong ultraviolet radiation field that is incident upon a population of gas (neutal atomic and molecular) and dust. A subclass of photodissociation regions, reflection nebulae, are an ideal place to study molecular hydrogen as a diagnostic of the physical conditions present. Fluorescent emission is produced when a molecule absorbs an ultraviolet photon and produces a characteristic spectrum as it cascades back to the ground state energy. By observing both the ultraviolet and infrared spectra of reflection nebulae, we may unambiguously determine the excitation mechanisms present, either fluorescent or thermal in nature. I propose to study a handful of reflection nebulae using both existing and future observations to determine the processes at work, thereby better constraining models of energy transport and distribution in photodissociation regions.

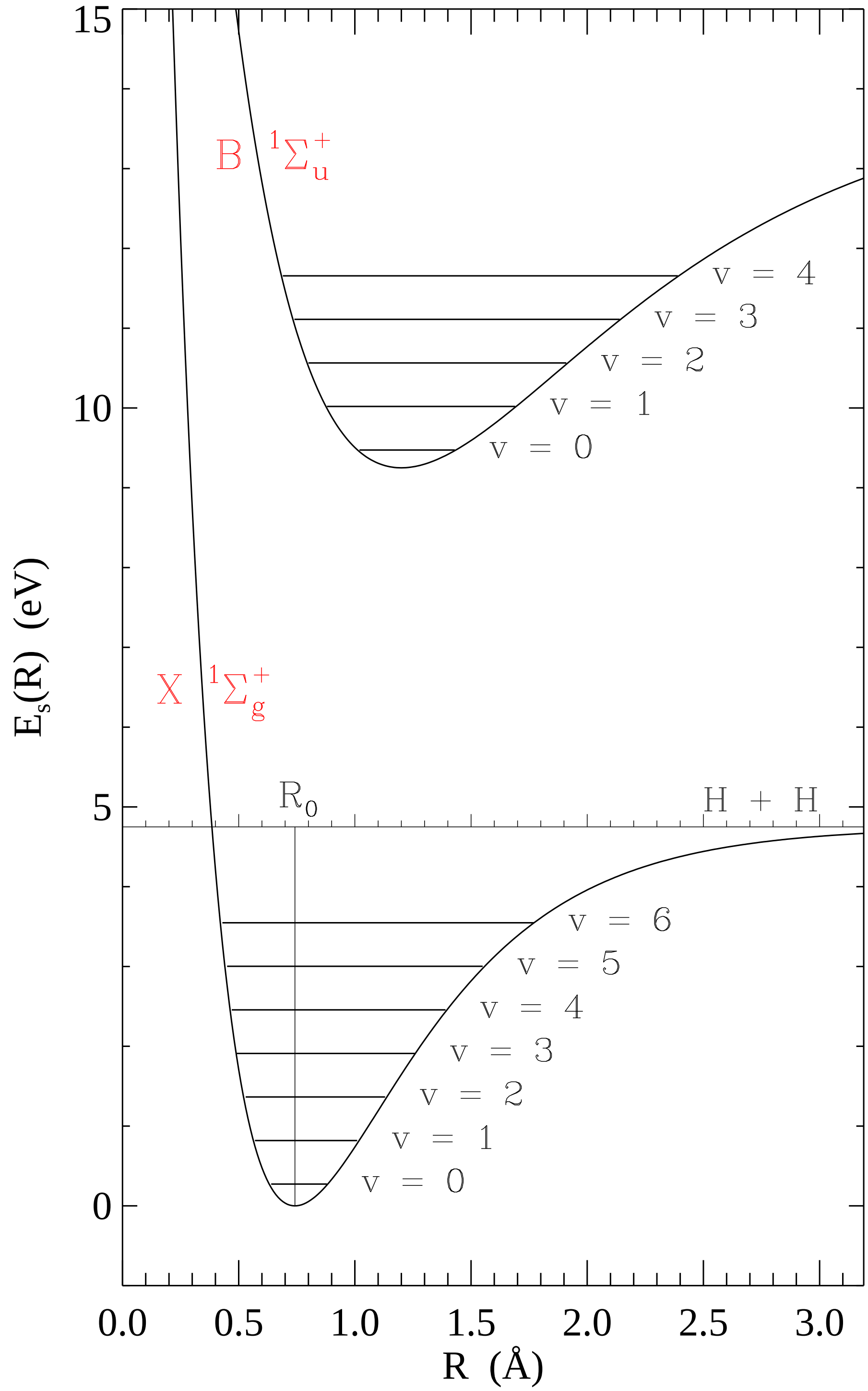

Figure 1: Energy level diagram of molecular hydrogen showing several vibrational levels in both the ground ($X^1\Sigma_g^+$) and first excited ($B^1\Sigma_u^+$) electronic states. After being excited into the higher electronic state, a population of molecules will produce a fluorescent emission spectrum as they return to the ground electronic and vibrational energy levels (the $B - X$ transition gives rise to the Lyman band system). *Figure courtesy of Aki Roberge.*

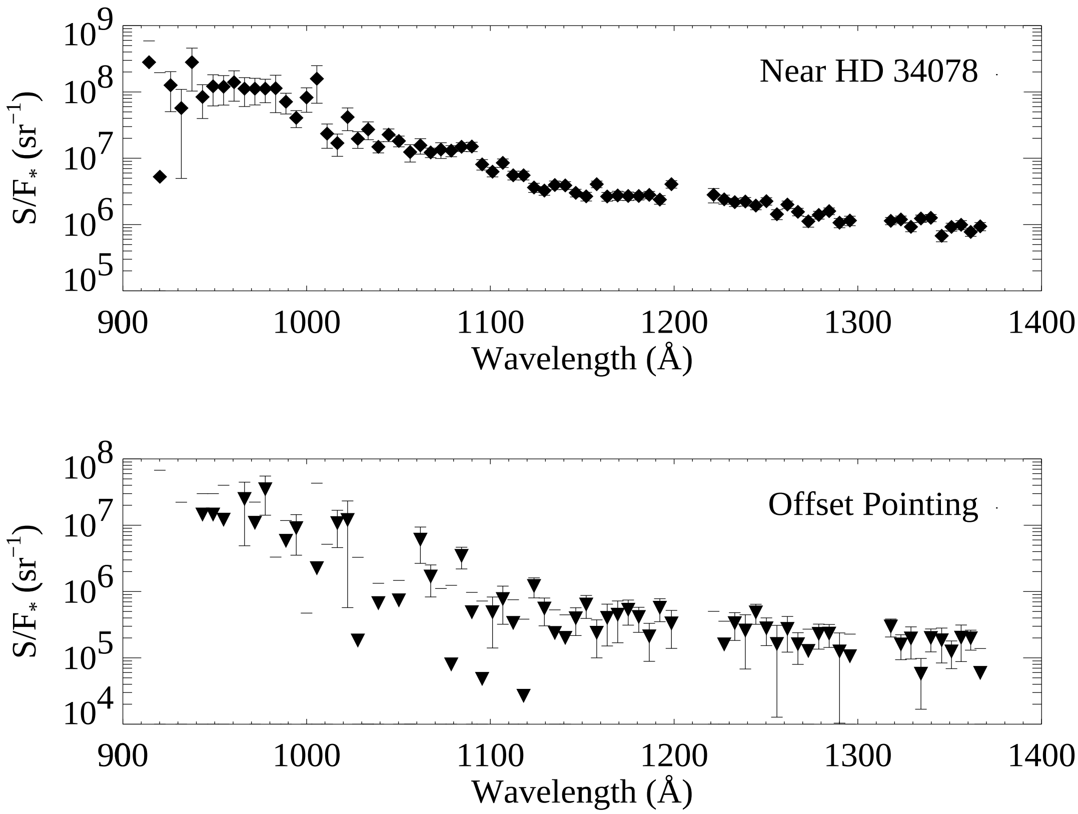

Figure 2: The ratio of nebular surface brightness to stellar flux rises by two orders of magnitude over the bandpass of the JHU rocket experiment, 900 – 1400 Å. The nebular offset pointing exhibits a similar trend despite the decreased signal-to-noise.

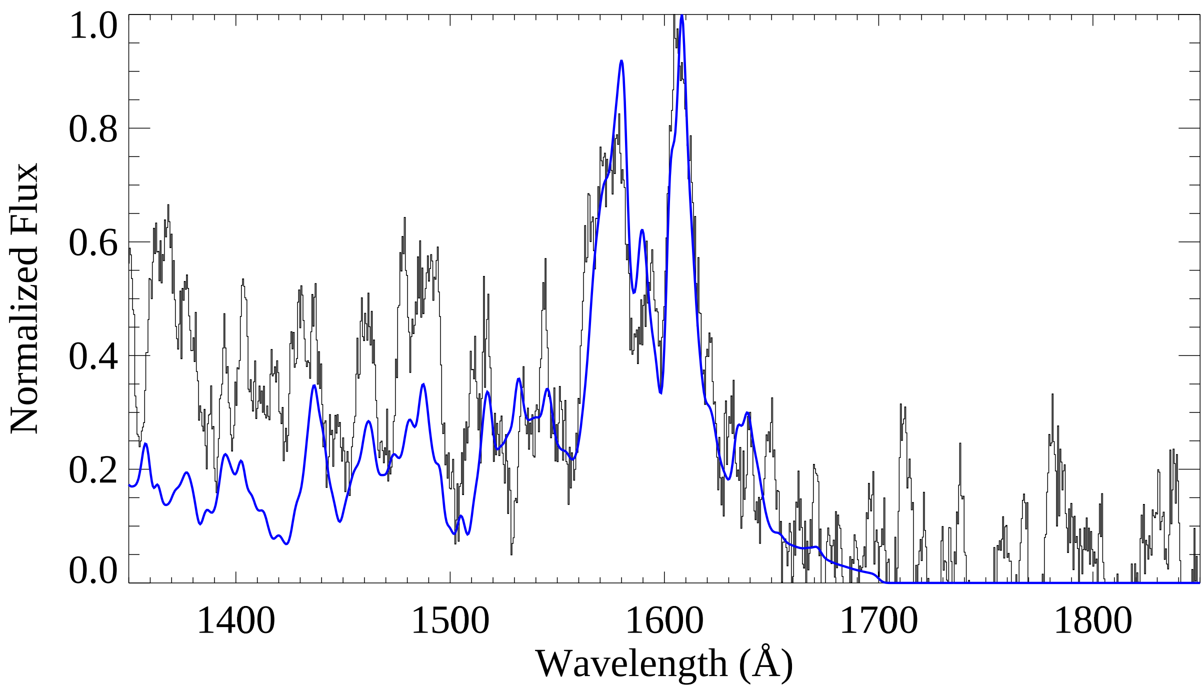

Figure 3: An unpublished HUT spectrum of NGC 7023, showing the double-peaked emission feature near 1600 Å. A modified Wolven model of fluorescent H_2 emission is overplotted in blue. The scattered light continuum was assumed to have the same shape as HD 200775 after applying a scale factor and multiplying by $\lambda^{0.25}$, following Witt et al. 1989.

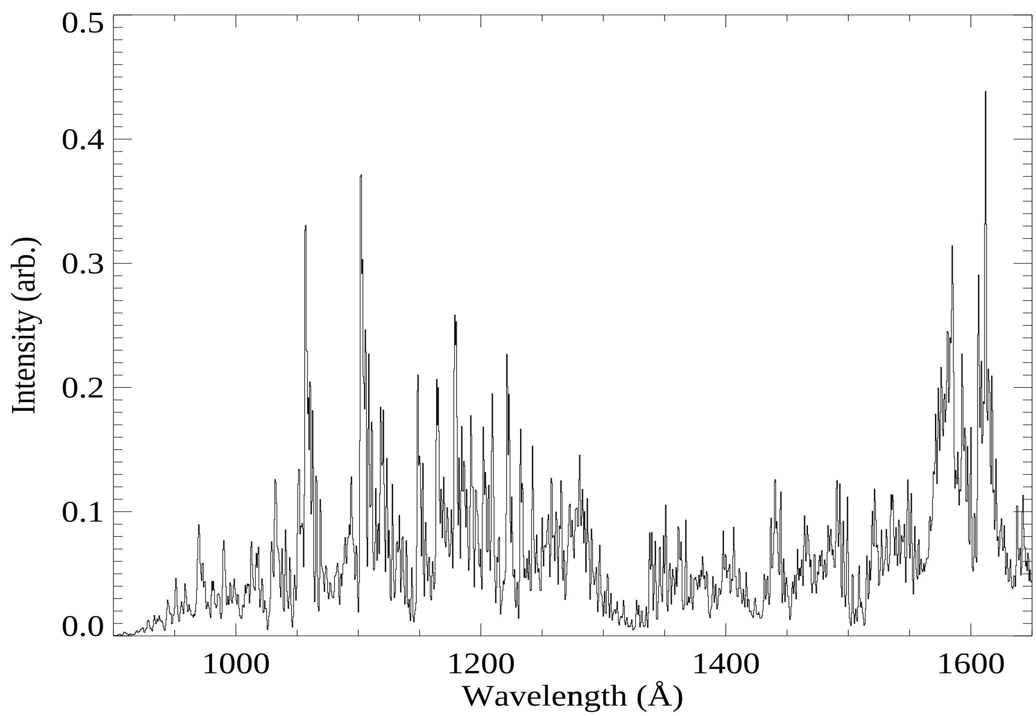

Figure 4: A modified Wolven model of a fluorescent H_2 emission spectrum. It has been convolved with the expected instrumental profile of a spectrograph under development by the Johns Hopkins University Sounding Rocket Group, see Section 4. This profile does not take into account in-flight jitter.

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