Neutral Hydrogen in the Terrestrial Thermosphere and Exosphere: Ground-Based Observations

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Science Motivation:

The exosphere (or geocorona) is the interface between the Earth's neutral atmosphere and interplanetary space. Our understanding of this important interface — through observations of its mean state and its response to external forcing — will provide important benchmarks as we seek to develop a complete picture of our complicated space-atmosphere system. This poster highlights recent contributions of ground-based, high-throughput interference spectroscopy to the study of this important region.

Geocoronal Balmer series emission line observations are made throughout the night; the base of the Earth's shadow is used as a first-order probe of the exosphere's altitude structure. Major areas of scientific focus include: (1) high resolution observations of the geocoronal hydrogen Balmer α line profile and its relation to excitation mechanisms, effective temperature, and exospheric physics; (2) retrieval of geocoronal hydrogen parameters such as the hydrogen column abundance [H], the hydrogen density profile H(z), and the photochemically initiated hydrogen flux φ(H); and (3) long term observations of the geocoronal hydrogen column emission intensity for the investigation of natural variability, such as solar cycle trends.

Fabry-Perot Spectrometers:

Fabry-Perot spectrometers are particularly well suited for detailed studies of extremely faint/diffuse geocoronal Balmer series emission because they are capable of simultaneously achieving high spectral resolution and high throughput (Hernandez, 1988; Roesler, 1974). High spectral resolution enables detailed line profile studies and is also necessary to unambiguously isolate the geocoronal line(s) from the ubiquitous Galactic (Balmer) background (Haffner et al., 2003). High throughput provides the temporal resolution needed to investigate, and limit, the variations in the emission due to changes in viewing geometry, local time, and atmospheric conditions. Although ground-based observations of geocoronal hydrogen have been made over the last several decades with increasing instrumental capabilities, the technique of Fabry-Perot charged-coupled-device (CCD) annular summing spectroscopy (Coakley et al., 1996) has enabled enormous gains in both the achieved signal-to-noise and temporal resolution of geocoronal Balmer series datasets.

ERAU operates two Fabry-Perot Spectrometers (FPS) to support this work: the **I**nvestigating **N**ear **Sp**ace **I**nteraction **Re**gions (INSpIRe) FPS, operating at the Pine Bluff Observatory (PBO), 15 miles West of Madison, Wisconsin, and the **W**isconsin **H**-**a**lpha **M**apper (WHaM) FPS at Cerro Tololo Inter-American Observatory (CTIO), Chile. Refer to Figure 1.

Fig. 1: (top) The INSpIRe FPS at Pine Bluff Observatory. (bottom) The WHaM FPS at CTIO, Chile. Near coincident INSpIRe / WHaM observations will begin this summer.

WHaM and INSpIRe are similarly designed 15-cm dual-etalon second-generation annular summing spectrometers (refer to Figures 2 and 3). WHaM can detect Balmer α emission as faint as 0.05 R in a 30 s exposure, covering a 200 km/s spectral region with 12 km/s velocity resolution from a 1 degree beam on the sky; with this sensitivity, hundreds of spectra can be collected in a single clear night. INSpIRe is capable of making Balmer α line profile observations with a signal-to-noise ratio of ~100 in under 10 minutes, covering a 75 km/s spectral interval with 3.5 km/s spectral resolution, from a 1.5 degree beam on the sky; on a good night, 20-40 spectra are obtained. WHaM has been in operation at CTIO since 2009; before that WHaM operated from Kitt Peak National Observatory (KPNO), AZ. INSpIRe began operating from PBO in June, 2022; PBO geocoronal Balmer α datasets date back to the 1970s (refer to Figure 4).

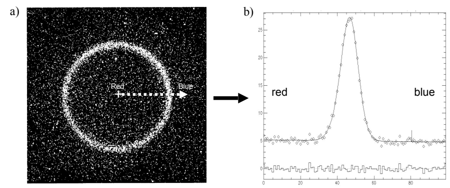

Fig. 2: Using the property that equal area annuli in the Fabry-Perot's fringe pattern correspond to equal spectral intervals, the CCD image of the fringe pattern (a) is divided into equal area annular bins, filtered to remove hot pixels, and averaged to obtain a line profile (b). This sample Balmer α line profile was obtained in 300s (each bin on the horizontal axis corresponds to a 0.75 km/s spectral interval). The total line intensity in this sample is ~ 5 Rayleighs (R), where 1 Rayleigh = 2.4 x 10^{-7} erg cm^{-2} s^{-1} str^{-1} at Balmer α.

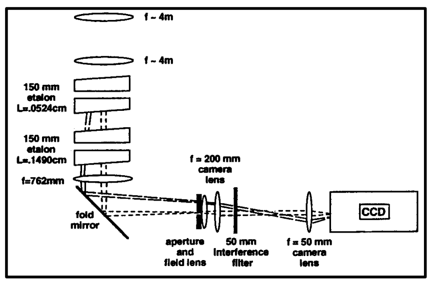

Fig. 3: Optical layout of the INSpIRe FPS. Entrance optics couple the Fabry-Perot to a plane mirror siderostat (not shown), allowing observations to be made in various look directions while avoiding regions of significant Galactic emission. Exit optics image the annular fringe pattern onto the CCD. The WHaM design is similar.

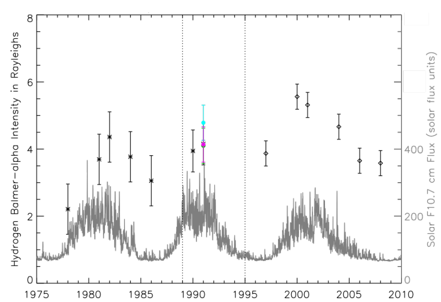

Fig. 4: Northern hemisphere mid-latitude hydrogen Balmer α intensity (points) at a shadow altitude of ~2800 km; these half-year bins represent many spectra and, in most cases, multiple nights. Comparison of 2000-2001 near-solar max observations with reanalysis of 1990-1991 observations suggests a likely increase in hydrogen emission intensity between these two near max periods (Nossal et al., 2019).

Line Profile Data:

High spectral resolution (INSpIRe) data is processed using a 9-component Gaussian fit, divided into two clusters. This two cluster model is convolved with an instrumental profile (measured several times a night using a Th 655.4 nm emission line) and fit to the observed spectra. The first cluster consists of two components representing two fine structure lines directly excited by solar Lyman β (in a fixed 2-to-1 emission ratio). The second cluster consists of seven cascade components (i.e., the full set of Balmer α fine structure emission), the emission ratios of which are based on the results of Meier (1995). The intensities of the two clusters and the spectral position of the profile are free fitting parameters. All 9 components are assumed to have the same width, the value of which is also a free parameter. Refer to Figure 5. Lower resolution WHaM data is fit with only two components representing direct solar Lyman β excitation.

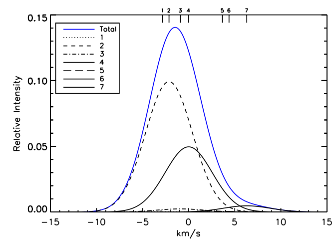

Fig. 5: Synthetic Balmer α profile for an effective temperature of ~ 800 K (6 km/s full width at half maximum) including a 5% contribution from cascade. The direct Lyman β excited components are labeled 2 and 4. The cascade emission is along fine-structure paths 1, 3, 5, 6, and 7. Note that components 7 and 3 contain 90% of the cascade emission (components 1, 5, and 6 are too faint to be easily seen in this figure) with the majority of cascade-excited emission on the red wing of the line profile. The centroids of the fine-structure components are included on the top of the plot with zero set at the location of component 4 (Roesler et al., 2014).

Model Analysis:

The lyao_rt code of Bishop (1999, 2001) was developed as a tool for the modeling of emissions by light atomic species extending out into the exosphere and is most commonly used for forward-modeling retrieval of excitation rates and densities of the emitting species. Using a parametric data-model comparison search procedure developed by Bishop et al. (2004), here we are exploring radiative transport (lyao_rt) model input parameters to map-out bounds for feasible forward model retrieved atomic hydrogen density distributions [H](z), fitting for both line width and intensity. Refer to Figures 6 and 7.

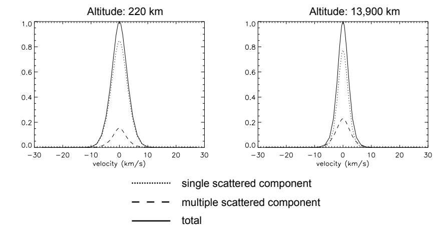

Fig. 6: Lyao_rt generated Balmer α profiles (normalized to the peak intensity) for two shadow altitudes, 220 km and 13,900 km. Observed Balmer α Doppler widths show a persistent narrowing of the profile with altitude (i.e., a decrease in effective temperature). Lyao_rt reproduces this trend, accounting for both single and multiple scattering contributions to the line.

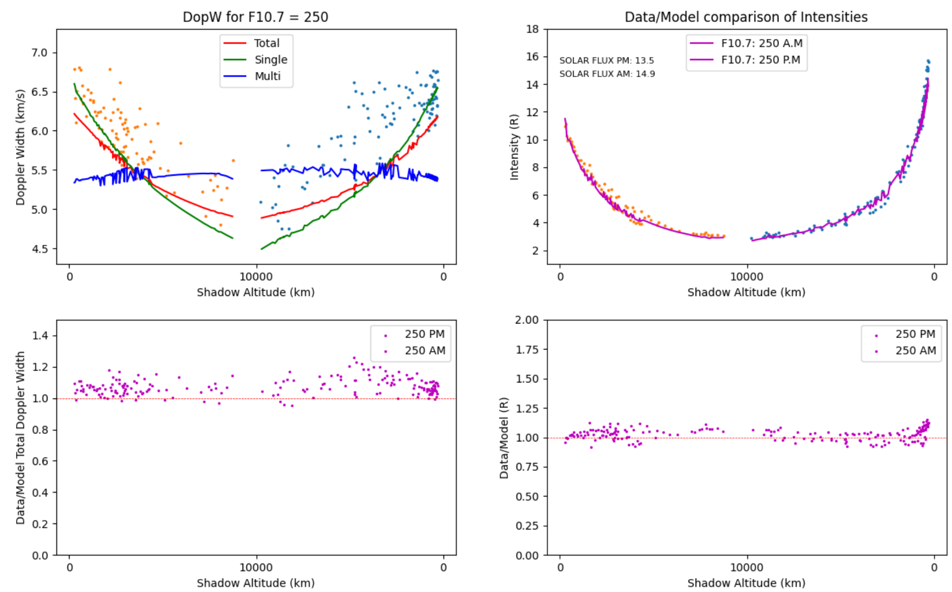

Fig. 7: Lyao_rt model "case b" (Bishop et al., 2004) candidate solutions compared to PBO Balmer α data. H profile parameters: n_{peak} = 1.0 x 10^{8}, n_{exo} = 2.8 x 10^{4}, flux = 3.0 x 10^{8}, T_{sat} = 750 K, n_{sat} = 6.8 x 10^{5}, MSIS background atmosphere with $F_{10.7}$ = 250. In general, low altitude intensities for the morning exosphere are typically 20% brighter than evening intensities for the same viewing geometry. Doppler widths (top left) show a persistent narrowing of the profile with altitude on all nights in which a wide range of shadow altitudes are sampled.