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Geocoronal Hydrogen Studies Using Fabry-Perot Interferometers
S.M. Nossal, E.J. Mierkiewicz, F.L. Roesler, J. Bishop, and R.J. Reynolds

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Ground-based Fabry-Perot observations of solar excited geocoronal hydrogen fluorescence emissions are one of the primary means of studying the neutral upper atmosphere [Atreya et al., 1975; Meriwether et al., 1980; Yelle and Roesler, 1985; Shih et al., 1985; Kerr et al., 2001a,b; He et al., 1993; Nossal et al., 1993, 1998, 2004; Bishop et al., 2001; Mierkiewicz, 2002; and references therein]. Excellent reviews of early ground-based geocoronal Balmer $\alpha$ observations are found in: Krassovsky et al. [1966], Krassovsky [1971], Donahue [1964, 1966], Tinsley [1974], Fahr and Shizgal [1983] and Kerr et al. [2001a]. Instruments onboard satellites and rockets also observe the geocorona, but these observations will not be the focus of this paper, except in terms of collaboration with ground-based passive optical instruments (see e.g., Bishop et al. [2004]).

The tenuous uppermost reach of the earth’s neutral atmosphere is commonly referred to as the exosphere or geocorona. For an overview of the geocorona with a historical perspective, see e.g., Chamberlain [1963], Tinsley [1974], Donahue [1977]. The exosphere is a unique region of the atmosphere characterized by low densities, long mean free paths, and non-Maxwellian orbital dynamics. In addition to its interesting physics, geocoronal hydrogen is important because of its involvement in many upper atmospheric chemical, photolysis, and charge exchange reactions. Geocoronal hydrogen is the by-product of lower and middle atmospheric hydrogenous species chemistry below involving radiatively important species such as methane and water vapor. As such, observations of thermospheric+exospheric hydrogen offer the potential as verification of the representation by atmospheric models of vertical coupling in hydrogenous species chemistry and as a possible upper atmospheric footprint of global change. Understanding of sources of natural variability such as the influence of the solar cycle is needed to characterize this region and to isolate signatures of natural variability from those due to human caused change. Scientific areas of focus for ground-based geocoronal research have included the following:

- High resolution observations of the geocoronal hydrogen Balmer $\alpha$ line profile and its relation to excitation mechanisms and exospheric dynamics.

- Retrieval of the hydrogen column abundance.

- Long term observations of the geocoronal hydrogen column emission intensity for the investigation of natural variability, such as solar cycle trends, and of potential anthropogenic change due to increases in atmospheric concentrations of warming gases.

We will begin by discussing the technique of Fabry-Perot spectroscopy as applied to geocoronal hydrogen observations, including strategies for obtaining data of sufficient precision and scope to address these science questions. We will use Wisconsin geocoronal hydrogen emission observations to illustrate capabilities and
challenges associated with using Fabry-Perot Interferometer annular summing spectroscopy for addressing the three research areas outlined above. Of particular emphasis will be the role of advances in passive optics that have led to higher precision, and how that has impacted the science. We will conclude with recommendations based on an assessment of outstanding science questions and observational issues. A companion paper by Kerr et al. will discuss observations made at Arecibo, P.R., the other site providing long term geocoronal Hα observations.

1 Observational Technique

Fabry-Perot spectrometers have become the instruments of choice, with few exceptions (e.g., Galand et al. [1994], Tinsley [1970]), for ground-based geocoronal hydrogen observations. Fabry-Perot spectrometers are particularly well suited for detailed studies of faint diffuse emissions as they are capable of simultaneously achieving high spectral resolution and high throughput (i.e., etendue) [Roesler, 1974; Roesler et al., 1979]. High spectral resolution isolates geocoronal from galactic Balmer α (now known to be significant in almost every direction on the sky [Reynolds, 1997]). High throughput provides high signal to noise for faint emission line studies with high temporal resolution in order to explore variations in the Balmer α profile due to changes in viewing geometry and solar depression angle. Mid-latitude geocoronal hydrogen observations now span 1977 to the present with some gaps in the instrumental record. A long term data set also has been obtained from the lower latitude Arecibo, PR Observatory starting in 1980 and continuing to the present [Kerr et al., 2001a,b].

Since geocoronal Hα emission is primarily excited by the line center portion of the solar Lyman β (1026 Å) flux, most of the Hα emission comes from above the Earth’s shadow, the height of which can be used to determine, to first order, the base of the column of Hα emission. The Hα column emission intensity observed by the Fabry-Perot is a measurement of the integrated volume emission rate along the observational line-of-sight, with the peak in the emission rate arising from just above the Earth’s shadow. This Hα column emission intensity is dependent upon the hydrogen density profile, the solar excitation flux, and the observational viewing geometry. A portion of the signal is also due to multiple scattering of Lyman β radiation below the Earth’s shadow. This contribution becomes increasingly significant for observations at higher shadow altitudes. Observations of thermospheric + exospheric Hα emissions require cross-calibrated and well-understood instrumentation, a stable calibration source, reproducible observing conditions, separation of the terrestrial from the galactic emission line, and consistent data analysis, accounting for differences in viewing geometry. Accurate calibration and consistent techniques are especially important for long term comparisons. We will briefly outline how we address these criteria in the sections that follow.

1.1 Observational Facilities

All of the geocoronal hydrogen observations made by Wisconsin observers have been made with similarly designed Fabry-Perot interferometers. All are ground-based, wide aperture (15 cm), double etalon configured instruments. Each was coupled to a pointing siderostat or situated next to another Fabry-Perot that was coupled to a pointing siderostat. In the later case, the instrument with the stationary zenith-pointing siderostat was cross calibrated with the instrument with the pointing capability. Earlier observations used a scanning photomultiplier detection system, while later observations make use of the Charge Coupled Device (CCD) camera for annular summing detection. Figure 1 shows a schematic of the annular summing high resolution Fabry-Perot currently located at the Pine Bluff, WI observatory.
There are currently two large aperture (15 cm), double etalon annular summing Fabry-Perot interferometers being used by Wisconsin observers for geocoronal studies. One instrument is located at the Pine Bluff Observatory (PBO) near Madison, WI. The PBO Fabry-Perot is of sufficient resolution ($R = \lambda/\Delta\lambda \approx 80,000$) to retrieve the geocoronal Balmer $\alpha$ line profile as well as the column emission intensity. The Wisconsin H$\alpha$ Mapper (WHAM) Fabry-Perot is a second instrument of lower resolution ($R \approx 20,000$) and is located at the Kitt Peak Observatory, near Tucson, AZ. WHAM has sufficient resolution to retrieve the H$\alpha$ column emission intensity and to separate the geocoronal line from the Doppler-shifted galactic line, but does not have high enough resolution to observe the H$\alpha$ line profile. Although WHAM is used primarily for making astronomical observations of interstellar medium emissions, the terrestrial emissions present in the WHAM astronomical spectra also offer a rich resource, in addition to dedicated WHAM geocoronal observations, for studying the geocorona.

1.2 Double etalon system

The double etalon configuration assists in isolating the geocoronal emission line. The second etalon [Roesler, 1974] enhances the instrumental contrast between the peak and the background of the instrumental profile, suppresses ghost emissions, and reduces parasitic light contamination. Ghost emissions arise because of the overlap of emission lines at other orders. When the etalon spacing is optimized to avoid overlap between the transmission orders of the high and lower resolution etalons, the free spectral range of the double etalon system can be extended beyond the bandpass of the interference filter [Roesler, 1974]. See, for example, Tuft [1997] and Haffner et al. [2003] for a description of the spacer ratio chosen for the Wisconsin H$\alpha$ Mapper Fabry-Perot and Mierkiewicz [2002] for the Pine Bluff, WI instrument.

1.3 Pointing and Tracking Siderostat

With a pointing siderostat observations can be taken in directions to avoid regions of bright galactic emission or where the doppler shift is small between the terrestrial and galactic H$\alpha$ emission lines. With a fixed mirror system, observations are restricted to time periods when the galactic emission overhead is faint or significantly doppler shifted (\(\leq \sim 15\) km/sec). The pointing capability also facilitates observations in multiple viewing geometries. Such observations are useful to constrain forward resonance radiative transfer modeling. In addition, a tracking siderostat is needed to observe nebular calibration sources for relative and absolute flux calibration. Tracking enables the Fabry Perot to keep the same galactic region in the field of view during the observation.

1.4 Annular Summing Spectroscopy

The development of the Charge Coupled Device camera in the late 1980s and its use as a detector enabled a dramatic increase in the sensitivity of Fabry-Perot observations of faint sources. Earlier observations used photomultiplier detectors to count photons passing through the center bandpass of the Fabry-Perot. The CCD enabled the Fabry-Perot interference pattern to be imaged and light to be collected in all spectral elements simultaneously and in addition took advantage of the high quantum efficiency of the CCD detector [Reynolds et al., 1990; Coakley et al., 1996].

In the photomultiplier scanning system (see for example, Roesler [1974]), light from the central bandpass is collected by the photomultiplier by focusing the Fabry Perots interference pattern onto the plane of the exit aperture coupled to the photomultiplier. The size of the sampling element is defined by the size of the exit aperture, and chosen to match the desired spectral resolution element (see e.g., Roesler, [1974]).
wavenumber of the passband is changed via a scanning system whereby the pressure of the gas between
the etalon plates is changed slowly. The slight change in pressure causes a small change in the index of
refraction of the gas between the etalon plates and in the resulting optical path difference. The spectral
profile is obtained by sequentially scanning over the wings and peak of the emission line.

A principle advantage of CCD annular summing detection is that light is collected simultaneously in all
spectral elements [Coakley et al., 1996]. The Fabry-Perot's annular interference pattern is focused onto the
CCD chip; refer to Figure 2. After image processing, the CCD image is converted into a spectral profile
using an annular summing algorithm. This technique uses the property that equal area annuli within a
Fabry-Perot's interference pattern correspond to equal spectral elements. Pre-processing of the geocoronal
Fabry-Perot data includes bias subtraction, filtering to remove cosmic rays, and dark subtraction.

After pre-processing, the CCD image is converted into a spectral profile (see e.g., Figure 6 and 7) by
averaging the pixel intensity within concentric equal area annuli. The area of the central and concentric
annuli is chosen so as to sample several times within a resolution element. This summing procedure is
sensitive to the choice of the center of the ring pattern. We refine the choice of the center with an iterative
process. We sum an image of a narrow Thorium laboratory lamp line used to obtain the instrumental
profile by varying the choice of center. We vary the center along successively finer grids to obtain the
narrowest width for the instrumental profile. The center locations on the finest grid vary by 0.1 pixel
[Coakley et al., 1996].

The remaining step before fitting is to divide the spectral profile by that obtained from a white light flat
field. A flat field is used to correct for vignetting within the instrument and to a lesser extent pixel-to-pixel
variation across the CCD chip. We obtain an approximate flat field by shining a white light off of a white
mat board with a scattering surface located above the siderostat on the roof outside of the observatory
[Mierkiewicz, 2002; Nossal, 1994]. In practice it is very difficult to obtain a spectrally uniform, spatially
uniform source to serve as a flat field. We annular sum the image of the flat field using the same algorithm
as used for the observations. Finally we divide the observational spectral profile by the annular summed
flat field.

Coakley et al. [1996] detail instrumental considerations for using Fabry-Perot CCD annular summing
spectroscopy for aeronomy applications. The paper details resolution, and read and photon noise con-
siderations in the calculation of signal-to-noise gains for different applications. Using the specifications
for available cryogenically cooled CCD cameras at the time, Coakley et al. predicted typical sensitivity
gains of 10-30 for a set of extreme low and high light level types of aeronomy observations. Demonstration
observations used a fold mirror to take alternating high resolution geocoronal Hα line profile observations
using photomultiplier and CCD detection [Coakley et al., 1996; Nossal et al., 1997, 1998]. Predictions of a
factor of 10-15 savings in integration time for night sky geocoronal Hα observations were consistent with
these field tests [Coakley et al., 1996].

The Wisconsin Hα Mapper Fabry-Perot and the Wisconsin Pine Bluff Fabry-Perot are designed specifi-
cally for the technique of annular summing spectroscopy [Tuft, 1997; Mierkiewicz, 2002]. One gain of these
designs is a large spectral range imaged on the CCD which enables observations of the nebular calibration
emission line and wings, and of multiple lamp lines that can be viewed simultaneously for a more accurate
determination of the instrumental dispersion. In addition, the larger spectral range also enables a more
careful fitting of galactic emission in the wings of the geocoronal Hα line profile that in turn improves the
fit to the terrestrial Hα line profile [Mierkiewicz, 2002].
1.5 Instrumental Profile

Images of thorium lines produced in a thorium-argon (Th-Ar) hollow cathode lamp were used to measure the instrumental profile (IP), to determine the center of the Fabry-Perot fringe pattern, and for spectral scale (dispersion) calibration.

Thorium is a heavy, even-even nucleus, and is therefore a very narrow emission with no hyperfine structure [Roesler, private communication]. The predicted width of the thorium emission produced in a hollow cathode lamp (with a typical discharge temperature of $\sim 1000$ K) is 0.42 km/s; $\sim 1/10$th the expected measured line width for a spectrometer working at $R \approx 80,000$. Thus, the thorium emission can be used as a measure of the spectrometer’s achieved spectral resolving power, where it is assumed that all observed broadening to the thorium emission is due to instrumental effects. (Neglecting the inherent width of the thorium emission introduces a negligible $-4$ K temperature bias [Nossal et al., 1997].) The average measured fwhm of a thorium 6554 Å emission line by the PBO Fabry-Perot was found to be 3.75 km/s (i.e., $R = 80,000$).

The thorium 6554 Å line is used as a measure of the instrumental function as it is the brightest thorium line in the spectral vicinity of Balmer $\alpha$. As such, reflectivity and phase shifts in the etalon coatings are not expected to have a dramatic effect on 6554 Å emission relative to Balmer $\alpha$ (6563 Å) [Roesler, private communication]. The thorium IP is convolved with a model fit to the data in order to account for line broadening due to the instrument from that of the of the actual emission feature under study.

It is important to measure the IP at the same position on the chip where the spectral feature under study is observed. In this way uncertainties due to imperfections in the optical imaging of the ring pattern onto the CCD will be minimized [Mierkiewicz, 2002; Haffner et al., 2003; Coakley et al., 1996].

1.6 Dispersion calibration

The dispersion across the CCD chip can be calculated by imaging the emissions from two narrow laboratory lamp lines on the CCD with accurately known wavelength difference. One method involves using a hydrogen-deuterium (H–D) lamp. The Balmer $\alpha$ line of hydrogen differs in wavelength from the Balmer $\alpha$ line of deuterium by 1.78 Å (82 km/s). By scattering the light from the H–D lamp off a white card above the Fabry-Perot, and knowing the spectral interval between the observed H and D lines, the corresponding spectral interval per annular bin is determined. This method works well for lower resolving power systems such as WHAM (see e.g., Tufte [1997]), but the broad H–D emission lines and their complex line ratios, which depend on the properties of the lamp, lead to unacceptable uncertainties at high resolving powers [Roesler, private communication].

Estimates of the spectral interval per data point can also be determined by taking two images of a known calibration line (e.g., thorium 6554 Å) at two different absolute chamber pressures (i.e., the theoretical shift in spectral interval with a change in pressure can be determined, and thus the corresponding measured shift in ring position can be used to calculate the spectral interval per annular bin). To fully exploit this technique a fringe counting method, e.g., using a Michelson gas refractometer with a well determined fringe interval, is needed in order to get enough accuracy in the change in $\mu$ with the change in pressure (see e.g., Coakley [1995]).

In the case of the high resolution Fabry-Perot system at Pine Bluff, the spectral interval per sample interval was determined with a method analogous to the H–D lamp technique, only in this case images of two sets of two well known narrow thorium lines were used: 6560 Å and 6559 Å, 6565 Å and 6554 Å. Knowing the spectral intervals between these lines allowed the spectral interval per sample bin (0.75 km/s) of the PBO system to be determined. This technique was made possible due to the optical design of the
PBO Fabry-Perot in which a 75 km/s spectral interval (and hence a number of thorium calibration lines) could be obtained in one exposure. This technique of determining the spectral interval per sample interval was not possible with the CCD/annular-summing demonstration instrument, and represents a significant improvement over earlier spectral calibration.

1.7 Intensity Calibration

The absolute intensity of the thermospheric+exospheric Hα column emission is calibrated through comparisons with Hα emissions from standard astronomical nebular calibration sources, all of which have been tied to the North American Nebula (NAN). Nebular calibration is internally consistent and is used for calibrating all of the Wisconsin-based atmospheric, planetary, and astronomical hydrogen Hα observations. Nebular calibration offers long term stability and like the geocorona, nebulae are spatially extended line rather than continuum emission sources. The use of nebular calibration minimizes uncertainty due to atmospheric extinction corrections since both the geocoronal hydrogen and the nebular calibration sources are outside of the Earth’s atmosphere. Corrections are made for differences in atmospheric extinction due to differences in slant path between the observational and calibration look directions using the following algorithm.

\[
I_{\text{geo}} = I_{\text{NAN}} \left[ A_{\text{geo}} / A_{\text{NAN}} \right] e^{(-\tau \cdot \sec Z_{\text{NAN}})} / e^{(-\tau \cdot \sec Z_{\text{geo}})}
\] (1)

In this equation, \(I_{\text{geo}}\) and \(I_{\text{NAN}}\) are the intensities and \(A_{\text{geo}}\) and \(A_{\text{NAN}}\) are the integrated areas of the geocoronal Hα column emission and of the nebular Hα emission, respectively. The zenith angles of the geocoronal and nebular calibration observations are respectively \(Z_{\text{geo}}\) and \(Z_{\text{NAN}}\). The atmospheric extinction coefficient, \(\tau\), is approximately 0.078 for a clear sky at the Kitt Peak Observatory and approximately 0.14 for a clear sky at the Pine Bluff, WI Observatory. The atmospheric extinction coefficient can be measured by observing a nebular calibration source throughout the night and monitoring the intensity of the measurement versus the zenith angle of the observation. The absolute intensity calibration of the WHAM observations has been tied to a 1 degree patch (centered at right ascension 20h 57m 59s and declination +44d 34’ 50”) of the North American Nebula whose intensity is 800 R ±10%. There is about a 5% uncertainty in the relative calibration due to night to night variability in the transmittance of the atmosphere at Kitt Peak. The North American Nebula has been calibrated for Hα using standard stars [Scherb, 1981] and has also been checked against a blackbody source [Nossal, 1994]. The accuracy of this calibration has also been corroborated with a comparison to the Southern Hα Sky Survey Atlas [Gaustad et al., 2001]. Accurate pointing capabilities are required to consistently repeat an intensity calibration using the same patch of the North American Nebula.

There are small differences in intensity of the North American Nebular calibration associated with differences in the field of view of the instrument. The intensity of the 0.8° patch of the North American Nebula observed by the pre-WHAM scanning Fabry-Perot at Pine Bluff was measured with standard stars to be 850 ± 50 Rayleighs. Mierkiewicz [2002] measured the intensity of the patch of NAN viewed by the 1.2° field of view high resolution Pine Bluff Fabry Perot to be 620 Rayleighs. Mierkiewicz [2002] made observations of NAN at different zenith angles and using a series of three iris settings to calibrate the 1.2° field of view from the primary 0.8° field of view standard star calibration [Scherb, 1981]. The iris was located above the etalons and in the focal plane of the sky. Differences in the nebular calibration associated with field of view must be considered when comparing data from different instruments.
1.8 Galactic Background and the WHAM galactic Hα survey

Balmer α emission from the galaxy can be of comparable magnitude or greater than that of the geocoronal Hα emission; refer to Figure 3. Isolation of the terrestrial emission therefore requires an accounting of the galactic emission. We try to plan our observations so that the Doppler shift between the geocoronal and galactic Hα emission lines is at least $\pm 15$ km/sec and/or that the pointing direction is greater than 30° in latitude away from the galactic plane. Such guidelines aid in our ability to avoid overlap between the galactic and geocoronal emission lines that is too great to be resolved. Accurate accounting of the galactic emission is important for retrieval of the geocoronal Hα column emission intensity and also for accurate fitting of the high resolution line profile.

The WHAM Hα galactic survey (see figure 4) can be used to obtain information about the Hα galactic emission intensity present in the WHAM observations. The WHAM website contains the results of the survey and documentation (http://www.astro.wisc.edu/wham/survey). The WHAM Integrated Survey Table (http://www.astro.wisc.edu/wham/survey) provides integrated galactic Hα intensity information over the local standard of rest velocity range (VLSR) of $-80 \text{ km/sec} < \text{vlsr} < 80 \text{ km/sec}$ for given galactic latitude and longitudes. The VLSR velocity is the deviation of the Local Standard of Rest from the geocentric zero velocity in units of km per second. The VLSR is the approximate doppler shift of the galactic emission from the geocoronal emission; however, this doppler shift may differ from the VLSR due to galactic dynamics. The map of the velocity integrated galactic intensity is also found at the above website.

1.9 Reproducible Observing Conditions

We only use observations made during clear skies and dark of the moon periods. Even high cirrus clouds can distort the retrieved intensities. The intensity calibration provides an additional check on the quality of the night. An unusual value for a nebular intensity calibration signals the possibility that the sky may not have been clear.

1.10 Tropospheric Scattering

Scattering of Hα radiation in the troposphere contributes to the line of sight column emission intensity observed by the Fabry-Perot. Radiative transfer modeling is needed to estimate corrections for this scattering within the troposphere. Wisconsin observers have estimated tropospheric scattering adjustments using a radiative transfer model developed by Leen [1979] (also see Shih et al. [1985]). This model uses a single scattering approximation and takes into account Rayleigh scattering by molecules, Mie scattering by aerosols, and the relatively small extinction from ozone absorption. For much of our analysis we have used only the primary measurements because we recognize the need for an improved scattering code for the higher precision measurements. When the thermospheric+exospheric Hα column emission intensities included in the solar cycle study by Nossal et al., [2004] were corrected for tropospheric scattering using the tropospheric scattering code of Leen [1979; Shih et al., 1985], the intensities were lowered by $14 - 26\%$, depending upon the viewing geometry. The conclusions of the paper were unchanged because the correction applied to both solar minimum and maximum conditions [Nossal et al., 2004]. With the guidance of Bishop [private communication, 2004] and the assistance of R.C. Woodward, we have been working on the development of an improved tropospheric scattering correction using the MODTRAN4 radiative transfer code. This code makes use of more current knowledge of tropospheric gas and aerosol distributions.
2 Geocoronal Balmer \( \alpha \) Fine Structure

Balmer \( \alpha \) (H\( \alpha \), \( \lambda \)6563) is the result of the \( (n = 3) \rightarrow 2 \) transition of atomic hydrogen and is composed of seven fine structure components (refer to Figure 5). Table 1 lists these transitions, their vacuum wavenumbers [Garcia and Mack, 1965], and the Doppler separation between the components. Geocoronal H\( \alpha \) fluorescence arises primarily from solar Lyman \( \beta \) (resonance) excitation. The only electric dipole allowed Lyman \( \beta \) transitions populate the \( 3^2P_{3/2,1/2} \) levels (refer to Figure 5). These levels subsequently decay 88% of the time to the ground state \( (1^2S_{1/2}) \), and 12% to the \( 2^2S_{1/2} \) state, the latter resulting in the H\( \alpha \) emission (see e.g., Bethe and Salpeter [1957], Table 15). Thus, H\( \alpha \) resonance-fluorescence is a blend of two fine structure components \( (3^2P_{3/2} \rightarrow 2^2S_{1/2} \text{ and } 3^2P_{1/2} \rightarrow 2^2S_{1/2}) \) in a 2:1 intensity ratio with a vacuum wavenumber line center of gravity of \( 15233.3280417 \text{ cm}^{-1} \) \( (\lambda_{\text{vac}} = 6562.741 \text{ Å}, \text{where the index of refraction at H}\alpha = \mu = 1.0002762 \text{ [Garcia and Mack, 1965])}. \) Note, the line center of gravity of the solar excited H\( \alpha \) resonance-fluorescence emission is blue shifted \( \sim 2.3 \text{ km/s} \) from the mean H\( \alpha \) wavelength \( (\lambda_{\text{mean}} = 6562.79 \text{ Å}) \) which contains the full suite of fine structure components [Garcia and Mack, 1965].

Typical geocoronal H\( \alpha \) intensities range from \( \sim 1 \text{–}10 \text{ Rayleighs}, \) where 1 Rayleigh \( R = 10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ str}^{-1} \) at H\( \alpha \).

Cascade processes result in additional fine structure components (not present in direct solar excitation) in H\( \alpha \). Solar Lyman lines (beyond Lyman \( \beta \)) excite geocoronal hydrogen atoms to energy states \( n > 3 \), some of which decay into \( n = 3 \), populating terms (in addition to \( 3P \)) which are not allowed by direct Lyman \( \beta \) excitation alone (i.e., \( 3S \) and \( 3D \)). These terms subsequently decay to \( n = 2 \), adding emission line components from all seven possible transitions to those produced solely by direct excitation. The net H\( \alpha \) emission is therefore a blend of nine total components: two from direct excitation, and seven from cascade, where the \( 3^2P_{3/2} \rightarrow 2^2S_{1/2} \text{ and } 3^2P_{1/2} \rightarrow 2^2S_{1/2} \) transitions include both direct and cascade contributions. The cascade excitation is estimated to be \( 5 \pm 3\% \) of the total intensity based upon recent observations by Mierkiewicz [2002] and revised estimates by Meier [private communication, 2004]. Characterization of the cascade excitation is needed to separate it from non-Maxwellian perturbations to the geocoronal H\( \alpha \) line profile.

2.1 Fits to the data

Processing of the geocoronal Fabry-Perot data includes bias subtraction, filtering to remove cosmic rays, and “ring-summing”. In the case of the high resolution Pine Bluff Fabry-Perot, individual measured spectra are reduced using a 4-parameter fit procedure incorporating nine Gaussian line components grouped into two clusters and convolved with an instrumental profile (measured several times a night); refer to Figure 6. The first cluster contains the two fine structure lines directly excited by Lyman \( \beta \) scattering with a fixed 2-to-1 emission ratio. The second cluster contains the full set of seven Balmer \( \alpha \) fine structure components with lines set in the line ratios given in Meier [1995]. The transitions and spectral positions of the full set of seven Balmer \( \alpha \) fine structure components are listed in Table 1. The four free parameters in this fitting procedure are the total intensities of each of the two clusters, the line width (common to all fine structure components), and the spectral position. These fit parameters are tracked over the course of a night, over a new moon period, and over years.

Lower resolution WHAM column emission intensity observations are fit with either a model that includes the two directly (Lyman \( \beta \)) excited geocoronal H\( \alpha \) fine structure components or with an estimate model consisting of a single Gaussian fit; refer to Figure 7. These one or two component geocoronal H\( \alpha \) emission models are convolved with a WHAM instrumental profile and then fit to the geocoronal H\( \alpha \) emission line profile. Figure 7 shows a sample WHAM geocoronal H\( \alpha \) emission spectrum from an observation.
made on March 13, 1997 pointed toward a low galactic emission region of the sky. The exposure time was 30 seconds and the emission line intensity was 4.1 Rayleighs. Spectral displacements are expressed in velocity units with the “zero” velocity point placed at an arbitrary location. In addition to the two component fit to the geocoronal emission, the fit also includes the galactic emission (0.20 R) shown here at 105 km/sec (in relation to the arbitrary “zero” velocity point) and a faint atmospheric emission (0.13 R) at 57.5 km/sec [Hausen et al., 2002; Nossal et al., 2004].

In both the Pine Bluff and WHAM data fits, the model parameters are iterated subject to the above constraints to produce a least squares, best-fit to the data using the voigt-fit code of R.C. Woodward [personal communication, 2004].

3 Observations of the Geocoronal Hydrogen Hα Line Profile

The first application of a Fabry-Perot annular summing spectrometer to the study of the geocoronal Balmer α emission demonstrated the instrument’s potential for exploring the intricacies of Balmer α at high spectral resolution [Coakley et al., 1996; Nossal et al., 1997, 1998]. Although the CCD/annular-summing demonstration observations contributed to an important new understanding of geocoronal Balmer α excitation and emission, the data set was limited in coverage, and instrumental vignetting compromised the full advantage of the annular summing technique [Nossal et al., 1997].

In 1999 the entrance and exit optics of the demonstration instrument were completely redesigned and the instrument was rebuilt in order to minimize vignetting and facilitate improved intensity, wavelength, and linewidth calibration [Mierkiewicz, 2002; Mierkiewicz et al., 1999]. This newly designed CCD/annular-summing Fabry-Perot is currently installed and operated at the University of Wisconsin’s Pine Bluff Observatory (PBO). A signal to noise ratio of approximately 50 is obtained for a typical geocoronal Balmer α intensity in a ten minute integration, covering a 75 km/s (∼1.6 Å) velocity interval with 3.75 km/s (∼0.08 Å) velocity resolution ($R = \lambda/\Delta\lambda \approx 80,000$), from a 1.5 degree beam on the sky. Observations are limited to two week periods centered around new moon in order to avoid spectral contamination from scattered sunlight. An extensive geocoronal Balmer α data set of approximately 1500 spectra over 71 nights was obtained during the first two years of operation at PBO (2000-2001); this data set will be discussed here.

The entire set of 2000-2001 PBO intensity data set is presented in Figure 8. In the lower panel of Figure 8 the 2000-2001 PBO Balmer α intensity data set is divided into observations conducted before and after midnight local time (i.e., pm and am observations). On average, dawn intensities are observed to be ∼20% brighter than dusk intensities for similar shadow altitudes. The magnitude of this dusk to dawn intensity asymmetry is consistent with the earlier observations by Tinsley [1970] and others, and it seems likely that the majority of the variation in Balmer α intensity observed from PBO is associated with diurnal variations in the hydrogen density, with additional contributions due to viewing geometry effects and possibly seasonal variations.

3.1 Line Profile Data

Analogous to Figure 8, nearly the entire set of Balmer α Doppler width data is presented in Figure 9. In this case only spectra in which |VLSR| ≥ 10 km/s are included in the figure. Although most geocoronal observations from PBO were restricted to regions away from the galactic plane (toward regions of low galactic emission), the addition of a VLSR data cut reduces the uncertainty associated with Doppler width determination due to galactic contamination. The presence of even a small amount of galactic Balmer α emission can have a large impact on the derived geocoronal line width. The WHαM Balmer α galactic
survey is being explored as a way to explicitly model the galactic component which is present at some level in almost every geocoronal spectrum. Employing an accurate model of the galactic component in the geocoronal fitting procedure has great potential for reducing uncertainties associated with geocoronal line profile determination in the presence of a galactic background.

A decrease in Doppler width with shadow altitude is a persistent feature in every night of PBO observations in which a wide range of shadow altitudes was observable; refer to Figure 9. The extent and quality of the 2000-2001 PBO Balmer α data set enables a detailed investigation into this line profile narrowing which was first reported by Meriwether et al. [1980] and later observed by Yelle and Roesler [1985] and Kerr et al. [1986]. The Nossal et al. [1997] CCD/annular-summing demonstration observations show significantly less profile narrowing with altitude than the other observers. Although the narrowing trends observed in the 2000-2001 PBO data set are in good qualitative agreement with Meriwether et al. [1980], Yelle and Roesler [1985] and Kerr et al. [1986], significant line profile perturbations detected by some of these observers (e.g., Meriwether et al. [1980], Kerr et al. [1986]) or the Lorentzian-like profiles observed at very high shadow altitudes (e.g., Yelle and Roesler [1985]) were not detected in the 2000-2001 PBO data set.

In terms of an effective temperature, the decrease in Doppler width with altitude displayed in Figure 9 represents a ∼500 K decrease, starting at ∼850 K near 500 km, and decreasing with shadow altitude to ∼350 K near 20,000 km. Although it is possible to speculate on potential sources of this decrease (e.g., contributions from satellite atoms at high shadow altitudes or multiple scattering of Lyman β into the earth’s shadow illuminating cooler hydrogen below the exobase) detailed radiative transport modeling is necessary for full interpretation. In fact, as anticipated by Meriwether et al. [1980] and Yelle and Roesler [1985], and definitively concluded by Anderson et al. [1987], the effects of multiple scattering on the line profile cannot be neglected when interpreting this type of observation. Based on initial model-data comparisons it seems unlikely that the decrease in Doppler width with shadow altitude can be fully explained in terms of multiple scattering contributions to the line, although multiple scattering does affect the overall magnitude of the line width.

3.2 Preliminary Lyao_rt Comparisons

The radiative transport code lyao_rt (see e.g., Bishop [2004]) is being used in PBO line profile interpretation. Lyao_rt was developed as a tool for the modeling of emissions by light atmospheric species extending out into the exosphere and is most commonly used for forward-modeling retrieval of excitation rates and densities of the emitting species. Of particular relevance to this program is the code’s ability to output hydrogen emission line profiles for both the singly and multiply scattered components of the Balmer α (and Balmer β) emission.

Preliminary lyao_rt Doppler width model runs, corresponding to a sample PBO data set (03-03-00) are included here for illustrative purposes; Refer to Figure 10. Lyao_rt line widths were computed for lines-of-site which corresponded exactly to the observational geometry at which the 03-03-00 PBO observations were conducted. In addition, lyao_rt was run twice, with slightly different input parameters (mainly adjusting the time of the observation and the exobase hydrogen density), in order to mimic a “pm” and “am” exosphere; refer to Table 2. The hydrogen distributions in each run were loosely based on solar minimum parameters in Bishop et al. [2001] and therefore are not necessarily representative of exospheric conditions on 03-03-00 (i.e., near solar maximum). The MSIS “background” parameters employed by lyao_rt (i.e., the background atmospheric density distribution and its temperature structure) were, however, representative of 03-03-00. Refer to Table 2 for a list of lyao_rt model inputs used in this analysis. It is important to stress that no attempt was made to obtain absolute model-data agreement (i.e., a detailed forward-model
analysis was not undertaken).

The first lyao\_rt model run, specifically the corona.f subroutine, employed an isothermal exosphere at the temperature of the (MSIS) exobase; model-data Doppler widths for the isothermal case are shown in Figure 10a. Inspection of Figure 10a immediately reveals a number of interesting insights into the exosphere. Most notably is the difference in line width as a function of altitude between the model output and PBO observations, with the model displaying very little change in Doppler width as shadow altitude increases. As the isothermal version of lyao\_rt includes contributions from multiple scattering, but assumed an isothermal exosphere, it is clear that multiple scattering contributions alone are insufficient to explain the observed decrease in line width as a function of shadow altitude (Figure 10d). That is, although multiple scattering becomes a larger fraction of the total Balmer $\alpha$ emission with increasing shadow altitude, and the multiple scattered component of the emission is dominated by contributions from the cooler denser regions of the thermosphere, it is unlikely that the magnitude of this contribution can be made large enough, in any realistic way, agree with the narrowing trend observed in the PBO data set.

Contributions from multiple scattering do, however, lower the overall magnitude of the Balmer $\alpha$ line width. The single-scattering component (solid line) in Figure 10a is representative of the conditions in the exosphere, which, in the isothermal case, is assumed to be at the temperature of the MSIS exobase (refer to Table 2). When the singly and multiply scattered contributions to the Balmer $\alpha$ profile are combined, the lyao\_rt line width is noticeably cooler than the MSIS exobase temperature, as are the PBO observations; refer to Figure 10a. It is clear from this example that multiple scattering cannot be neglected when attempting to determine an exobase temperature from observations of Balmer $\alpha$ Doppler widths, even when the shadow altitude is near the exobase.

Lyao\_rt Doppler width analysis was repeated employing a version of corona.f which explicitly accounts for the nonisothermal conditions of the exosphere [Bishop, private communication]. The lyao\_rt inputs used in this analysis were identical to those used in the isothermal case. Inspection of Figure 10b reveals that the multiple scattered contribution to the line width remains nearly the same as in the isothermal case. This is expected as the isothermal and nonisothermal model runs employed the same hydrogen distribution, and therefore the same contributions to the line from multiple scattering (contributions which are dominated by emissions below the exobase, and therefore not altered by the new nonisothermal representation of the exosphere).

The singly scattered contribution is significantly different in the nonisothermal model than the isothermal case, and in reasonable qualitative agreement with the PBO observations. Much like the PBO the observations (Figure 10d), the lyao\_rt generated profiles (Figure 10b) display a distinct narrowing with shadow altitude. The majority of this narrowing is due to “gravitational cooling”, where ballistic atoms trade kinetic energy for potential energy as they travel upward into the exosphere, where they eventually slow to a stop before returning to denser regions below. The net effect is a ballistic atom population with slower radial velocities as altitude increases, and thus narrower Doppler widths as a function of shadow altitude. Also apparent in Figure 10b is that profile contributions from multiple scattering seem to flatten the overall decrease in total line width with increasing shadow altitudes.

A second run of the nonisothermal version of lyao\_rt was conducted in which all model inputs were identical to the previous examples with the exception of the flux parameter $\Phi(H)$. In this run $\Phi(H)$ was decreased from $3 \times 10^8$ cm$^{-2}$ s$^{-1}$ to $1 \times 10^8$ cm$^{-2}$ s$^{-1}$, a value more appropriate for solar maximum conditions [Bishop, 2001]. Refer to Figure 10c. Lowering $\Phi(H)$ had little effect on the singly scattered contribution to the Balmer $\alpha$ profile, as the singly scattered contributions to the emission primarily arise from within the exosphere itself. The “temperature” of multiply scattering component did, however, increase. This increase is presumably due to the associated decrease in hydrogen content in the model thermosphere (below 300
km), refer to Figure 11. Less thermospheric hydrogen results in less multiple scattering contributions to
the emission, particularly from this “cooler” region of the atmosphere.

Altering the magnitude of the flux parameter has an effect on the multiple scattering contribution to
the emission, and hence to the net Doppler width of the emission and its variation with shadow altitude.
This correspondence will be explored further in future analysis, in particular with regard to its potential
as an additional model constraint in order to obtain unique solutions to the upper-thermospheric, lower-
exospheric hydrogen distribution through forward-modeling.

3.3 Cascade

In their initial CCD/annular-summing geocoronal demonstration observations, Nossal et al. [1998] defini-
tively detected an enhancement to the red wing of the basic geocoronal solar Lyman $\beta$ resonance-fluorescence
(on the order to $\sim$10%, sometimes more, sometimes less) which they determined to be consistent with cas-
cade. This number was slightly higher than the $\sim$7% contribution predicted by Meier [1995], and much
higher than Meier’s recent revision downward to $\sim$4% based on the SOHO/SUMMER data of Warren et
al. [1998] [Meier, private communication]. Shemansky et al. [1999] have argued that photoelectron impact
excitation of the $3S$, $3D$ terms may be sufficient to enhance the $3S \rightarrow 2P$ and $3D \rightarrow 2P$ components
of Balmer $\alpha$ as needed to explain the net $\sim$10% red wing enhancement reported by Nossal et al. [1998],
particularly in view of the of the recent reduction in cascade contribution by Meier.

As previously discussed, each Balmer $\alpha$ spectra in the PBO data set was fit with a two cluster Gaussian
model which takes into account both direct solar excitation and contributions to the emission due to
cascade. The PBO data set indicates that the cascade contribution at Balmer $\alpha$ is $\sim$5%; refer to Figure
12. (Note, these observations, and those of Nossal et al. [1998], are near solar maximum, Meier’s cascade
calculations are based on solar measurements conducted near solar minimum.)

Only 18% of the PBO data initially included in Figure 8 was deemed useful for cascade studies. Two
limits were used to restrict the full PBO data set in order to achieve an accurate cascade determination:
$VLSR < -10$ km/s or $VLSR > 35$ km/s, and a pointing direction at least $\pm 60^\circ$ in galactic latitude (i.e.,
well out of the galactic plane). These requirement helped to ensure that even small amounts of galactic
emission (i.e., at the sub Rayleigh level) were not mistakenly fit as cascade contributions. The improved
optical system of the PBO Fabry-Perot, with its 75 km/s spectral baseline centered on Balmer $\alpha$, allows
better identification and characterization of galactic emission; refer to Figures 13a and 13b.

The arrows in Figures 13a and 13b indicate the position of the LSR at the time of the observation; 25
km/s to the red of the geocoronal line in Figure 13a and -25 km/s (to the blue) in Figure 13b. The galactic
emission is rather broad ($\sim$25 km/s), thus even when significantly Doppler shifted from the geocoronal line
center, galactic contributions from the wings of the galactic emission may overlap and be mistakenly fit
as geocoronal emission. Also, in regions of the sky where the galactic emission is known to be extremely
faint (i.e., sub Rayleigh), if the emission is near the red wing, this sub Rayleigh signal can look exactly
like cascade emission which is also a sub Rayleigh component to the Balmer $\alpha$ emission. Although care
was taken in the original CCD/annular-summing observations by Nossal et al. [1998] to avoid regions with
high amounts of galactic emission, without the benefit of an extended baseline it is possible that at least
some galactic emission went unnoticed. Furthermore, even though many observes have relied on $VLSR$ to
restrict their observations to times/look-directions when the galactic component is Doppler shifted away
from the geocoronal line, the extended baseline of the PBO Fabry-Perot and the high sensitivity of the
annular summing technique made it possible to search for galactic contributions after the observations are
conducted, and quantify the magnitude of the galactic “contamination”.

Explicit modeling of the galactic component, will allow less restrictive cascade data cuts, and eventually
a more thorough investigation into the cascade emission. Theory predicts a shadow altitude dependence on cascade contributions; this limited (i.e., restricted) cascade data set is currently inconclusive on this account. (At higher shadow heights, where a larger portion of the Balmer α emission is attributable to multiple scattering, the cascade contribution to the line is expected to be less important than at lower shadow heights where the dominant emission arises from single scattering.)

In addition to the galactic emission masking cascade contributions, recent work by Hausen et al. [2002] indicates that faint atmospheric lines (some of which are time dependent) populate the spectral regions about the Balmer α emission. As the full potential of this data set is explored, these faint lines will be explored with the PBO Fabry-Perot as suggested by Reynolds [Private communication].

4 Coincident Balmer α and Balmer β Observations

The success of the annular summing technique has prompted a new look at the geocoronal Balmer β emission first isolated by Reynolds et al. [1973]. Initial test observations with the WHαM and PBO annular summing spectrometers have demonstrated the potential of this technique for a detailed study of the geocoronal Balmer β emission. Given the differing transport properties of Lyman β and Lyman γ, measurements of the variation of both Balmer α and Balmer β with solar depression angle (SDA) and viewing geometry, see e.g., Figure 14, has the potential improve upper atmospheric hydrogen distribution determination. For example, (lyao_ rt) model atomic hydrogen density profiles can be systematically varied in order to obtain consistent fits to both Balmer α and Balmer β. Fitting, in terms of replicating the SDA, OZA, and AZI variations of both emissions, will provide a tight constraint on lyao_ rt atomic hydrogen distributions that are independent of the estimates of solar line center fluxes and calibration against astronomical standards [Bishop, private communication].

Also, an important use of Balmer β intensity observations in conjunction with Balmer α line profile observations stems from the fact that Lyman γ (which populates the 3S parent term of Balmer α) is the major contributor to the cascade emission seen in Balmer α (see e.g., Meier [1995]). Thus, Balmer β intensity observations provide a direct measure of the total excitation by Lyman γ and therefore a direct estimation of the predominate cascade contribution at Balmer α. Cascade contributions based on Balmer β estimates of Lyman γ excitation can then be directly compared with measurements of the cascade emission from Balmer α line profile observations in which the cascade component is explicitly fit. Is the cascade model the total picture, or are there additional excitation mechanisms or undetected spectral contamination? The identification of other excitation mechanisms may be possible through the presence of fine-structure components in excess of the cascade contribution predicted by Balmer β and measured via Balmer α.

4.1 Balmer β and Exospheric Physics

The presence of cascade emission at Balmer α, which is mainly clustered on the red-wing of the profile, masks potential kinetic signatures associated with the various exospheric particle populations. Observations of Balmer β may aide in “unveiling” this mask as the same exospheric kinematics affect both emissions but their fine structure components differ.

Further, Balmer β offers great promise for the direct observation of geocoronal conditions from the ground; this is due to the upper atmosphere being more optically thin at Lyman γ than at Lyman β (by a factor of 0.37) and also because the pure absorption of Lyman γ is dominated by strong N2 photoabsorption which places the Lyman γ “black level” significantly higher than that of Lyman β (160 km vs 102 km).
which results in significantly less multiple scattering of Lyman $\gamma$ since Lyman $\gamma$ photons do not penetrate as far down into thermosphere where the hydrogen density is as high as that “seen” by Lyman $\beta$. Hence, even though Balmer $\beta$ intensities are roughly an order of magnitude smaller than Balmer $\alpha$ [Reynolds et al., 1973], the single scattering component (a measure of the true exospheric line profile) will be the dominant profile feature at Balmer $\beta$.

5 Retrieval of the Hydrogen Column Abundance

Retrieval of the hydrogen abundance requires the use of forward modeling because the hydrogen column emission intensity is a complicated function of the hydrogen density profile, the solar excitation flux, and radiative transfer including the contribution of multiple scattering below the Earth’s shadow. We have been using the lyao rt global resonance radiative transfer code of Bishop [1999] to compare Fabry–Perot column emission intensity observations taken in multiple viewing geometries with calculated intensities. The hydrogen column abundance is a more robust retrieval as finding a unique solution for the hydrogen density profile requires additional constraints. Bishop et al. [2004] have been using near coincident ground-based and satellite data sets to investigate limits to input parameters used in forward modeling to enable more accurate abundance retrieval.

The lyao rt global resonance radiative transfer code of Bishop [1999] accounts for nonisothermal conditions and multiple as well as single scattering excitation by solar Lyman emissions, but this code does not account for the complications of cascade, collisional excitations, or exospheric kinetics. The lyao rt radiative transfer calculations are typically performed with thermospheric temperatures and density profiles of the major thermospheric species ($N_2$, $O_2$, O) obtained from the Mass Spectrometer Incoherent Scatter–90 (MSIS–90) upper atmospheric empirical model [Hedin, 1991], however the code could also be coupled to other model atmospheres. The atomic hydrogen density profile, $[\text{H}]$, at thermospheric altitudes is handled by direct integration of the vertical diffusion equation, as has been done in several past studies [e.g. Anderson et al., 1987; He et al., 1993], which typically results in thermospheric column abundances larger than those generated by MSIS (sometimes by as much as factors of $\sim 2$). Principal input parameters to the lyao rt code are the thermospheric upper boundary exobase atomic hydrogen density, the mesospheric peak atomic hydrogen density, and the photochemical upward flux. The portion of exospheric hydrogen atoms on satellite orbital trajectories is described via two additional additional free parameters. The user also provides the geographical location from which the observation was made and solar geophysical information (F10.7, Ap indices) from which the MSIS thermospheric density and temperature profiles are constructed.

Forward modeling comparisons of calculated and observed hydrogen emission intensities yield a “best fit” hydrogen column abundance. Case study comparisons with global resonance radiation transport modeling results indicate that the WHAM geocoronal data have sufficient signal-to-noise to distinguish and rank goodness of fit for different model scenarios to within 5% in their associated upper atmospheric hydrogen column abundance [Nossal et al., 2001].

Incorporation of the vertical diffusion equation at thermospheric altitudes and improved measurements of solar Lyman line excitation fluxes [Warren et al., 1998] led to a resolution of a historical “factor of two” discrepancy between satellite and ground-based measurements [Bishop et al., 2001]. Understanding this discrepancy corroborated the observations and was a prerequisite to being able to use ground-based and satellite observations together as constraints to forward modeling.

Bishop et al. [2004] used near-coincident ground-based Balmer $\alpha$ from the Pine Bluff, WI Fabry-Perot interferometer and geocoronal hydrogen Lyman $\alpha$ and Lyman $\beta$ observations from the Espectrografo Ultravioleta extremo para la Radiacion Difusa (EURD) instrument on the Spanish MINISAT-1 satellite as
constraints to the lyao\_rt code. Both sets of observations were taken during the dark of the moon period in March 2000. They developed a data–model comparison search procedure to test an extensive grid of input parameters. Bishop et al. [2004] were able to identify sets of parameters that produced good fits to both the ground-based and satellite observations. Their search criteria included requirements for agreement between morning and evening solar line center fluxes derived from both data sets, and for data/model ratios close to one for both data sets at and at different viewing geometries. A search of thousands of sets of input parameters led to only about 50 sets of input parameters that fit the selection criteria [Bishop et al., 2004]. Examples of four candidate solutions from the search procedure are included in Figure 15.

Bishop et al. [2004] found the tightness of the constraints provided by their data–model comparison search to be surprising given the crudeness of the parameter binning and remaining corrections to be made to both the PBO and EURD data sets. For the Fabry–Perot observations, these corrections include improved tropospheric scattering estimates and any reduction to the uncertainty in the value of the absolute intensity calibration. Additional information about exospheric physics obtained from high resolution line profile data can also be incorporated into the lyao\_rt code to improve the retrievals. It is anticipated that refined searches building upon the course grid searches of Bishop et al. and involving smaller parameter bins will lead to further constraints on forward modeling inputs. Additional constraints on the suite of input parameters to the lyao\_rt code are needed to obtain a unique solution for hydrogen column abundance retrieval from Fabry-Perot observations in multiple viewing geometries and for hydrogen density profile retrieval from near simultaneous observations at multiple wavelengths.

6 Long Term Hydrogen H\(\alpha\) Column Emission Observations

Fabry-Perot interferometers are being used to investigate the influence of the solar cycle variation on the Earth's upper atmosphere. Understanding this influence is important for determining the basic state of the region, as well as for distinguishing between natural variability and possible longer term climatic trends.

Geocoronal H\(\alpha\) column emission data sets spanning two solar cycles exist both from the lower latitude Arecibo Observatory [Kerr et al., 2001a,b, and references therein] and from midlatitudes by Wisconsin observers [Nossal et al., 2004, 1993; Mierkiewicz, 2002; and references therein]. The Arecibo data set is described in the companion paper. The midlatitude observations are from Stoughton, WI and Pine Bluff, WI observatories, both outside of Madison, WI, and from the Kitt Peak Observatory near Tucson, Arizona. We have some observations during the same dark of the moon period from Wisconsin and Kitt Peak [see Figure 19]. Collectively, these observations span 1977 to the present, with some gaps in the instrumental record. The more recent measurements use annular summing spectroscopy and have higher signal-to-noise. Observations of thermospheric + exospheric H\(\alpha\) column emissions by the Wisconsin H\(\alpha\) Mapper (WHAM) Fabry-Perot (Kitt Peak, Arizona) during solar cycle 23 show a statistically significant solar cyclical variation, with higher emissions observed during solar maximum conditions. These data add to the Wisconsin long term midlatitude H\(\alpha\) emission data base. The high signal-to-noise WHAM observations corroborate suggestions of a solar cycle trend seen in Wisconsin H\(\alpha\) emission observations over the previous solar cycle (cycle 22). As described in the observational technique section, long term comparisons of thermospheric + exospheric H\(\alpha\) emissions require cross-calibrated and well-understood instrumentation, a stable calibration source, reproducible observing conditions, separation of the terrestrial from the galactic emission line, and consistent data analysis, accounting for differences in viewing geometry.
6.1 Solar Cycle 22 Study

Observations of the geocoronal H\textalpha\ column emission were made by Wisconsin observers over solar cycle 22 using a double-etalon, pressure-scanned, 15-cm Fabry-Perot Interferometer \cite{Nossal et al., 1993, and references therein}. These observations were made using the same instrument, first located at the Physical Sciences Laboratory located in Stoughton, WI, and then moved to the Pine Bluff, WI Observatory. Both locations are within 20 miles of Madison, WI. All of the observations were calibrated using standard astronomical nebulae. The 1990 and 1991 observations were part of the NSF sponsored CHARM campaign. Many of the earlier observations were taken specifically for geocoronal studies \cite{Shih et al., 1985; Yelle et al., 1985}. Some of the observations included in the long term data set were the terrestrial emission lines present in astronomical observations.

The data set used to investigate solar cycle trends was limited to observations taken within 30\degree to the zenith, where uncertainties due to atmospheric extinction corrections were minimized. A major challenge when comparing data is that the viewing geometry is the factor with the largest influence upon the geocoronal H\textalpha\ column emission intensity. To make an estimate correction for the large intensity variation with viewing geometry, the data were normalized by dividing the observed H\textalpha\ column emission intensity by model predictions for the viewing geometry of the observation. We chose to use predictions from the model by \textit{Anderson et al.} \citep{1987} because it did a good job of predicting relative variation in H\textalpha\ column emission intensity with viewing geometry.

The \textit{Anderson et al.} \cite{1987} model uses a Monte Carlo models of geocoronal hydrogen distributions as inputs to a radiative transfer model of solar Lyman \beta\ excitation in the thermosphere and exosphere. The \textit{Anderson et al.} model predicts the H\textalpha\ column emission intensity that would be observed from the ground at a midlatitude site for a variety of viewing geometries. The model contains three submodels corresponding to periods of minimum, medium, or maximum solar activity levels. After analyzing the data set using the appropriate submodel for the solar conditions of the observations, we then reanalyzed the data using only the solar maximum submodel (see Figure 16). We chose to use this submodel as the reference for comparing all of the observations because it produced observation to model ratios closest to unity \cite{Nossal et al., 1993}.

The analysis indicated that any solar cycle variation present in the Wisconsin geocoronal H\textalpha\ column emission observations over solar cycle 22 was significantly less than that predicted by the \textit{Anderson et al.} model \cite{Nossal et al., 1993}. Intensities were higher during solar maximum periods, but did not show a statistically significant variation in absolute intensity over the solar cycle. However, the relative intensity variation with viewing geometry did show a solar cycle dependence. In addition, the observations were not inconsistent with an upward trend in intensity, however any such trend could not be seen with statistical significance.

6.2 WHAM Solar Cycle 23 Observations

Like other Wisconsin-based instruments, WHAM is a ground-based, 15 cm double-etalon Fabry-Perot. WHAM is remotely operated, semi-automated, and has optics especially designed for using the CCD-based (charge coupled device camera) annular summing technique \cite{Coakley et al., 1996}. WHAMs resolving power \((\sim 25,000)\) is sufficient for separation of the terrestrial emission from the Doppler-shifted galactic line and for retrieval of the H\textalpha\ column emission intensity.

WHAM is used primarily for making astronomical observations of interstellar medium emissions \cite{Reynolds, 1997; Haffner et al., 2003}. The terrestrial spectra present in these observations also provide a rich resource for studying geocoronal atomic hydrogen H\textalpha\ emissions. As for all of the other Wisconsin-based
atmospheric, planetary, and astronomical hydrogen H\(\alpha\) observations, WHAM is calibrated using nebular calibration. The absolute intensity of the thermospheric + exospheric H\(\alpha\) column emission is calibrated through comparisons with specific patches of standard astronomical nebular sources, all of which have been tied to a 1° patch (centered at right ascension 20h 57m 59s and declination +44d 34’ 50”) of the North American Nebula (NAN) [Haffner et al., 2003; Nossal et al., 2004]. Corrections are made for differences in atmospheric extinction between the calibration and observational look directions. There is about a 5% uncertainty in the relative calibration of the WHAM H\(\alpha\) emission observations due to night to night variability in the transmittance of the atmosphere and a 10% uncertainty in the absolute calibration. The WHAM solar cycle study builds upon the 1997 WHAM study investigating daily variations in the geocoronal H\(\alpha\) column emission. The primary scientific mission of the WHAM instrument was to make an all-sky survey of the interstellar H\(\alpha\) emission [Haffner et al., 2003]. The majority of observations for this survey were made in 1997, with the acquisition of \(\sim\) 30,000 H\(\alpha\) emission spectra, spanning about 80 nights of observations. Since all of the galactic emission spectral data also contain the terrestrial H\(\alpha\) emission line, these measurements constitute a rich source of geocoronal data for investigating natural variability in the upper atmosphere.

Analysis of the 1997 WHAM geocoronal H\(\alpha\) observations shows only small day-to-day variations after shadow altitude variations are taken into account (see Figure 17). For example, at shadow altitudes of 2000 and 3000 km, the RMS scatter is within approximately \(\pm\) 20%; this variability is expected to be reduced with accurate accounting of the smaller-scale effects of observational slant path, zenith angle, and azimuth on the H\(\alpha\) intensity. This result is consistent with past midlatitude Wisconsin data sets.

For consistency, the data for the WHAM solar cycle 23 study were limited to observations taken during winter solstice conditions and in observing directions pointed toward low galactic emission [less than \(\sim\) 0.25 Rayleigh at H\(\alpha\)] regions of the sky. Such observations minimize uncertainty due to blending between the galactic and terrestrial H\(\alpha\) emission lines. The winter solstice typically offers the best sky conditions for observations, as well as longer nights. To insure consistent observing conditions, we only use observations taken during dark moon and clear sky conditions. A two Gaussian atomic physics model representing the two dominant fine structure transitions contributing to the geocoronal H\(\alpha\) emission was convolved with the instrumental profile and adjusted to find a best fit to the geocoronal H\(\alpha\) column emission observation [Nossal et al., 2004].

Figure 7 shows a sample geocoronal H\(\alpha\) emission spectrum from an observation made on March 13, 1997 pointed toward a low galactic emission region of the sky. The exposure time was 30 seconds and the emission line intensity was 4.1 Rayleighs. Spectral displacements are expressed in velocity units with the “zero” velocity point placed at an arbitrary location. In addition to the two component fit to the geocoronal emission, the fit also includes the galactic emission (0.20 R) shown here at 105 km/sec (in relation to the arbitrary “zero” velocity point) and a faint atmospheric emission (0.13 R) at 57.5 km/sec [Hausen et al., 2002; Nossal et al., 2004]. For this case of near maximum overlap between the geocoronal and galactic emission illustrated in Figure 7, the retrieved geocoronal H\(\alpha\) column emission differs by less than 4% from that retrieved when the galactic emission is not fit. This result provides an assessment of the upper limit of the uncertainty due to the presence of the galactic emission in these low galactic emission region observations. The retrieved geocoronal intensities also include the cascade excitation which is estimated to be 5 \(\pm\) 3% of the total intensity based upon recent observations by Mierkiewicz [2002] and revised estimates by Meier [1995; personal communication, 2004]. Neither the galactic emission, the geocoronal cascade excited emission, nor the presence of other low intensity atmospheric lines would account for the solar cyclic intensity difference shown in Figure 18 [Nossal et al., 2004]. Figure 18 displays thermospheric + exospheric H\(\alpha\) column emission intensities as a function of shadow altitude for changing
solar conditions. The shadow altitude is determined by the optical depth of solar Lyman \( \beta \) radiation (102 km) and the observational look direction. The shadow altitude is the viewing geometry parameter with the greatest influence on the geocoronal H\( \alpha \) column emission intensity. Small changes in intensity related to observational zenith angle and azimuth variations for a constant shadow height can also be detected [Nossal et al., 2001].

The 1997 observations (diamond symbol) displayed in Figure 18 were taken during solar minimum conditions, the 2004 observations during solar medium conditions (“o”) and the 2000-2001 observations (“+” and “x”) during near solar maximum conditions. The data included on this plot came from 23 nights of observations between December and the spring equinox. The solar minimum data (F10.7 69-76) are from 10 nights of observations, the solar medium data (F10.7 100-122) are from 5 nights of observations, and the near solar maximum data (F10.7 134-163) are from 8 nights of observations. We observe higher column emission intensities during solar maximum periods with the increase dependent upon viewing geometry. For example, at the mid range shadow altitude of 3000 km, WHAM geocoronal H\( \alpha \) column intensities are about 45% higher during solar maximum conditions than during near solar minimum conditions. The column emission intensities of the solar medium observations fall between those of the solar minimum and near solar maximum observations.

In the troposphere, Balmer \( \alpha \) photons from outside the line of sight scatter into the line of sight and enhance the retrieved column intensity. When corrections are made to the data of Figure 18 using the tropospheric scattering code of Leen [1979; Shih et al., 1985], the intensities are lowered by 14-26%, depending upon the viewing geometry. The solar cyclic difference persists because the corrections are applied to both solar minimum and maximum conditions [Nossal et al., 2004]. We have chosen to display the uncorrected primary measurements in Figure 9 because we recognize the need for an improved tropospheric scattering correction code.

Detailed modeling is needed to retrieve hydrogen column abundance information from the H\( \alpha \) column emission observations [Bishop, 1999]. As explained in more detail in section 5, case studies indicate that the hydrogen column abundance can be retrieved via forward modeling analysis [Bishop et al., 2001] with studies currently in progress to assess the sensitivity of retrievals to radiative transport forward modeling parameters [Bishop et al., 2004].

A careful examination of correction factors indicates that their magnitude is small compared with the observed solar cycle variation in the thermospheric + exospheric H\( \alpha \) column emission intensity. The higher signal-to-noise WHAM observations corroborate suggestions of a solar cycle trend in the H\( \alpha \) emissions seen in Wisconsin observations taken over the previous solar cycle (cycle 22) [Nossal et al., 1993]. The Wisconsin-based observations over solar cycle 22 also measured higher geocoronal H\( \alpha \) intensities during solar maximum periods; however past data were deemed to be of insufficient precision to make the variation statistically significant. The high signal-to-noise, and consistent calibration of the WHAM geocoronal H\( \alpha \) emission observations facilitate their use as benchmark data for comparisons with past and future data sets.

### 6.3 Comparison of observations from solar cycles 22 and 23

All the observations included in the solar cycles 22 and 23 studies were taken with similarly designed large aperture (15 cm) double etalon Fabry-Perot spectrometers, each coupled to a pointing siderostat. Our investigations have initially focused on separately analyzing observations taken with the scanning photomultiplier instrument located at Wisconsin [Nossal et al., 1993, and references therein] and with the annular summing spectroscopy Wisconsin H\( \alpha \) Mapper located at the Kitt Peak Observatory in Arizona [Nossal et al., 2004]. Though these data sets were independently analyzed, we looked to see whether any
similar or differing patterns existed in both. The WHAM observations of higher geocoronal Hα column emission intensities during the solar cycle 23 maximum were consistent with suggestions of a solar cycle trend seen in the Wisconsin Pine Bluff solar cycle 22 observations.

There are additional uncertainties associated with comparing data taken by different instruments. We have begun the process of exploring whether it might be possible to link the Pine Bluff and Kitt Peak data sets. Although both sets of observations are from midlatitude sites, there may be some geographical variation in geocoronal hydrogen. There also may be a difference in tropospheric scattering correction between the two observatories. Comparison of winter observations may minimize this uncertainty due to the typically clearer skies and drier conditions during these months. There are also small differences in field of view between the scanning Fabry-Perot used to make the solar cycle 22 observations, the annular summing high resolution Fabry-Perot currently located at the Pine Bluff, WI observatory, and the Wisconsin Hα Mapper Fabry-Perot. There may be additional uncertainties associated with comparing observations from a scanning and an annular summing Fabry-Perot.

Figure 19 shows observations taken with the high resolution Fabry-Perot Interferometer at Pine Bluff, WI and with the WHAM instrument from Kitt Peak, Arizona during the same dark of the moon period in February, 2000. The observations were independently analyzed and calibrated. The agreement between these two sets of observations corroborates the nebular absolute intensity calibration method. We plan to analyze more near simultaneous sets of observations from both instruments to investigate whether this agreement persists.

Additional strategies for comparing data from Solar Cycles 22 and 23 include using the Voigtfit spectral fitting code to reanalyze observations taken with the Wisconsin scanning Fabry-Perots. We currently use the Voigtfit code for our fitting and plan to compare the new fits with those made using earlier analysis codes. We also plan to compare observations of galactic regions taken with the scanning and two annular summing FPIs. Using the Wisconsin Hα Mapper galactic Hα survey, we plan to look for regions of uniform intensity and compare measurements of this intensity with all three instruments. Differences in the intensity measurements will help us to assess uncertainties associated with comparing data from the three instruments. The development of an improved tropospheric scattering correction code would provide information about predicted difference in tropospheric scattering contribution between the Wisconsin, Kitt Peak, and Arecibo observing sites.

6.4 Vertical Coupling of Hydrogenous Species

Hydrogen in the thermosphere+exosphere is the byproduct of chemical and photolysis reactions involving hydrogen containing species at lower altitudes. Methane and water vapor are considered to be especially important species because of their influence on the Earth’s radiative balance [Houghton et al., 2001]. Global sampling and ice core data have indicated that tropospheric methane concentrations have increased by about 150% since the industrial revolution [Houghton et al., 2001].

To first order, methane transport across the tropopause is the primary source of middle atmospheric water vapor. Most tropospheric water vapor freezes and falls at the cold tropopause, producing a freeze drying mechanism [Brasseur and Solomon, 1986]. Water vapor is transported through the tropopause, however, via energetic cumulus cloud activity in the tropics. The transport of molecular hydrogen through the tropopause is an additional source of middle atmospheric water vapor production.

Methane molecules are broken apart in the middle atmosphere mainly through oxidation reactions involving OH and O(1D) and by photolysis reactions [Brasseur and Solomon, 1986; LeTexier et al., 1988]. Subsequent series of reactions produce water vapor, H₂, OH, and H. Although there are different reaction paths, the carbon of the methane molecule passes through a stage in which it is part of a formaldehyde
molecule (CH$_2$O) [Brasseur and Solomon, 1986; LeTexier et al., 1988], making it an important molecule for future observations. Photoionization and photodissociation reactions involving H$_2$O, H$_2$, and other hydrogen containing species produce geocoronal hydrogen [Chamberlain and Hunten, 1987].

Hydrogen in the upper thermosphere is predicted to increase by about 40-50% in response to a doubling of tropospheric warming gases, principally methane, according to projections by Ehhalt [1986] and a global mean model study by Roble and Dickinson [1989]. Mesospheric water vapor was also projected to increase, along with methane, with the possibility of increased noctilucent cloud events due to the combination of increased mesospheric water vapor and cooler temperatures Roble and Dickinson [1989]. Roble and Dickinson [1989] doubled and halved concentrations of methane and carbon dioxide at 60 km in their global mean model of the coupled mesosphere, thermosphere, and ionosphere. They further simulated projected anthropogenic change by using lower boundary conditions from Brasseur and Hitchmans [1988] study of the response of the stratosphere to projected increases in trace gas warming species in the troposphere.

The Roble and Dickinson [1989] global mean model results showed cooling throughout the mesosphere and thermosphere changes in the composition of many trace species. The projected cooling is mainly caused by increases in carbon dioxide concentration, resulting in more radiative cooling to space in the middle and upper atmosphere, along with the trapping of heat in the troposphere. In the upper thermosphere, the temperature is projected to decrease by about 50K.

Though many of the sources of tropospheric methane emissions have likely been identified, there are uncertainties associated with the magnitude of these sources due to the difficulty of measuring global emission rates from sources in the biosphere [Houghton et al., 2001]. Natural sources of methane include wetlands and termites. Anthropogenic sources include fossil fuels, rice agriculture, ruminants, landfills, and biomass burning [Houghton et al., 2001]. The approximate average increase in methane concentrations over the last two decades of the 20th century was about 0.5% per year with a long term decline in the annual growth rate [Houghton et al., 2001; Dlugokencky et al., 1998].

Marsh et al. [2003] investigate water vapor in the mesosphere by analyzing almost a decade of both ozone and water vapor observations made by the Halogen Occultation Experiment (HALOE) on board the Upper Atmospheric Research Satellite (UARS). Their analysis showed an annual cycle in mesospheric water vapor at mid-latitudes that peaks in the summer, with an anti-correlated annual cycle in the ozone sunset observations. In addition, their analysis showed a decadal decrease in sunset ozone correlated with an increase in water vapor. These data were consistent with their three dimensional global chemical transport modeling sensitivity studies that pointed to the mechanism of water vapor photolysis producing hydrogen species that destroy ozone [Marsh et al., 2003]. The Marsh et al. [2003] study showed an increase in mesospheric water vapor of approximately 1% per year for HALOE observations between 1991 and 2001. The anticorrelation in the sunset ozone data corroborates the increase observed in the water vapor measurements.

Geocoronal hydrogen column emission observations may be able to contribute to our understanding of vertical coupling processes involving hydrogenous species. Geocoronal hydrogen is more globally mixed than are the locally dispersed sources of lower atmospheric hydrogenous species such as methane. In this sense, the upper atmospheric hydrogen observations may provide complementary information to measurements of hydrogenous species below.

The Wisconsin H$\alpha$ Mapper geocoronal H$\alpha$ column emission observations indicated a correlation of higher emissions with higher solar activity during solar cycle 23. The WHAM observations were consistent with a suggestion of such a trend in the solar cycle 22 observations. Retrieval of the hydrogen column abundance over differing solar conditions is important for improving our understanding of these solar cycle effects. Such retrievals are anticipated following establishment of tighter constraints on forward modeling
parameters [see Section 5]. Any upward trend in the solar cycle 22 geocoronal Hα column emission observations was not apparent with statistical significance but also was not inconsistent with predictions for a climatic upward trend. The WHAM data spanning only a little over half a solar cycle do not yet have the time extent to by themselves separate any longer term climatic signature from the solar cycle variation. As discussed in Section 6.3, we are in the process of exploring ways to link the two data sets so as to create a long term record including both solar cycles 22 and 23.

It may be possible to test model predictions for climatic increases in thermospheric+exospheric hydrogen using high signal-to-noise Fabry-Perot observations of hydrogen emissions. Such assessment will require a longer term record of high signal-to-noise Hα observations, retrieval of the hydrogen column abundance, and understanding of sources of natural variability.

The technique of Fabry-Perot observation of the Hα line profile is not well matched for assessing predicted temperature decreases in the upper thermosphere. Uncertainty associated with the temperature is proportional to the square of that associated with the width of the emission profile. Given typical exospheric temperatures of on the order of 1000 K, the predicted 50 K decrease in temperature represents about a 5% change in the temperature over a 100 year time frame. Given current measurement uncertainties, this change is too small to discern, especially if a data record is limited to only a couple of solar cycles. In addition, interpretation of the effective temperature is complicated because of non-Maxwellian dynamics and because the measurement is an integration over multiple altitudes.

7 Summary of Conclusions

- The magnitude and Doppler shift of the galactic Hα emission must be accounted for in order to accurately isolate the geocoronal emission line.

- A decrease in Doppler width with shadow altitude is a persistent feature in the 2000-2001 Pine Bluff, WI high resolution extensive line profile observations. These observations are in qualitative agreement with calculations from global resonance radiative transfer code lyao_rtt.

- A red–wing enhancement to the observed high resolution Hα line profile is consistent with calculations of cascade excited contribution to the line profile. Understanding the cascade excitation is necessary in order to isolate potential signatures of exospheric dynamics.

- Analysis of the 1997 WHAM geocoronal Hα observations shows only small day–to–day variations after shadow altitude variations are taken into account.

- There is a statistically significant solar cycle variation in the thermospheric + exospheric Hα column emission over the rise of solar cycle 23.

- We observe higher column emission intensities during solar maximum periods with the increase dependent upon viewing geometry. For example, at the mid range shadow altitude of 3000 km, WHAM geocoronal Hα column intensities are 45% higher during solar maximum periods.

- Neither the galactic emission, observational viewing geometry, atmospheric extinction, cascade excited emission, weather conditions, nor the presence of other low intensity atmospheric lines would account for the observed solar cyclic difference in column emission intensity.
• The high signal-to-noise WHAM observations corroborate suggestions of a solar cycle trend seen in \( \text{H} \alpha \) column emission observations from Pine Bluff, WI over solar cycle 22.

• There is agreement between mid latitude observations from Kitt Peak, AZ and Pine Bluff, WI during the same month, corroborating the nebular absolute intensity calibration.

8 Draft Recommendations Regarding Geocoronal Hydrogen Studies

8.1 Fabry-Perot Hydrogen Emission Observations:

• Balmer \( \alpha \) observations taken in multiple viewing geometries to constrain resonance radiative transfer forward modeling. This modeling is used to retrieve the hydrogen column abundance. Observations taken during near coincident satellite Lyman \( \alpha \) observations and/or ground based Balmer \( \beta \) observations provide additional model constraints.

• Continued high signal-to-noise \( \text{H} \alpha \) column emission intensity observations to investigate potential longer term natural and anthropogenic influences on the upper atmosphere, including those due to the solar cycle.

• High resolution FPI observations of the Balmer \( \alpha \) and Balmer \( \beta \) line profile. Near simultaneous observations at two wavelengths assists in isolating dynamical perturbations to the line profile from cascade contributions. Hydrogen atoms emitting at Balmer \( \alpha \) and Balmer \( \beta \) experience the same dynamical influences but the two emissions different fine structure contributions.

8.2 Instrument Recommendations:

• We recommend upgrades including the addition of a CCD camera and a second etalon to improve the sensitivity of FPIs making geocoronal hydrogen emission observations.

• We also recommend adding a pointing and tracking siderostat to minimize errors due to galactic emission overlapping with the geocoronal line.

• Improved calibration using nebular sources (requires a tracking siderostat).

8.3 Analysis Code Upgrades and Model Development:

• Continued development of an improved tropospheric scattering correction code to improve our estimation of the scattering contribution to the total column emission intensity. Such a code would also aid in comparing observations taken at different times of the year and at different observatories.

• Continued modeling efforts by WACCM, the TIMESGCM, and others to improve our understanding of vertical coupling of hydrogenous species, interactions between neutral and ion species, and the impact of sources of natural variability and anthropogenic change on the upper atmosphere.

8.4 Additional Observations:

• Satellite observations of high resolution solar Lyman line line profiles and intensities. The line center portion of the solar Lyman \( \beta \) line is the primary source of excitation of geocoronal \( \text{H} \alpha \). Higher order Lyman lines contribute to cascade and H\( \beta \) excitation.
• Observations of hydrogen containing species throughout the atmosphere to better understand vertical coupling. Such species include H\(^+\), methane, water vapor, molecular hydrogen, formaldehyde and hydroxyl.

• High resolution observations to better identify sub-Rayleigh atmospheric lines overlapping with the geocoronal hydrogen line profile.

9 Acknowledgments

We thank Matt Haffner, Steve Tufte, Nicole Hausen, Greg Madsen, and Robert Benjamin for sharing their WHAM observations. We are indebted to James Bishop for his collaboration and insights. We are grateful to R. Carey Woodward and Jeff Percival for assistance with analysis code development. We also thank John Harlander and Frank Scherb for their long term contributions to the Wisconsin geocoronal research program.
Figure 1: Basic optical diagram of the siderostat and dual-etalon Fabry-Perot annular summing spectrometer located at Pine Bluff Observatory (not to scale). Light from the sky is directed by the plane mirror siderostat through a “primary” lens L1, a collimating lens L2, and the etalons (E1 and E2). A series of post-etalon optics (L3, L4, and L5) image the primary and the Fabry-Perot fringe pattern onto the CCD. (The distance between L1 and L2 is ~4030 mm.) The effective focal length of the L1 L2 combination is 4028 mm. The field of view with a 150 mm field stop is ~2° (~1.5° for a 100 mm field stop and ~0.8° for a 56 mm field stop).
Figure 2: Geocoronal Balmer α fringe (CCD image, 512 × 512 array of 24 μm pixels, binned 2 × 2). Using the property that equal area annuli correspond to equal spectral intervals, images like this are converted to line profiles via annular-summing software. The radial position of the fringe was selected so that there was nearly equal spectral baseline to red (toward the fringe center) and blue (toward the edge of the CCD) of the emission. (10 minute integration, ns_4, 02-05-00.)
Figure 3: Sample WHαM Balmer $\alpha$ spectrum with galactic and geocoronal emissions. The telluric emission feature is the tall narrow peak ($\sim 6$ km/s $fwhm$), the broader emission ($\sim 20$ km/s $fwhm$) $\sim 45$ km/s to the red of the geocoronal line is galactic in origin. Careful observation planning minimizes the overlap of these two emissions. In addition, regions of significant galactic emission are generally avoided. The geocoronal emission intensity in this scan is 5.5 R; the spectra was obtained in 30 s. [Nossal et al., 2001]. (Although the velocity interval on this plot is correct, the zero point is placed at an arbitrary location.)

Figure 4: Wisconsin H$\alpha$ Mapper (WHαM) all sky survey of galactic Balmer $\alpha$ integrated intensities (37,565 spectra, velocity integrated emission from -80 to +80 km/s LSR) [Haffner et al., 2004]. This map was used to select regions of low galactic emission for geocoronal observations.
Figure 5: An energy level diagram showing the seven allowed Balmer α transitions of atomic hydrogen. For Lyman β excitation, indicated by the solid lines on the figure, only the $3^2P_{1/2,3/2}$ levels are populated, resulting in only two allowed Balmer α transitions (dashed lines on the figure). The dotted lines indicate the other five possible fine structure transitions, (not present in direct Lyman β excitation). Note, the energy spacing is not to scale.
Figure 6: Typical PBO nightsky spectrum (10 minute integration, ns_4, 02-05-00) and 9-component Gaussian fit. Although a 9-component Gaussian model is used in processing the Balmer $\alpha$ data, there are only four free model parameters: line width, line center, and the area of each of the two clusters used to represent direct and cascade excitation. Residuals (i.e., the difference between the data and fit) are also included. (Abscissa: bin number, where 1 bin = 0.75 km/s; bin 0 corresponds to the central sample bin, hence wavelength decreases from left to right.)

Figure 7: Sample WHAM H$\alpha$ spectrum in a region of low galactic emission (30 second exposure). Spectral displacement is expressed in velocity units. Zero velocity is placed at an arbitrary location. In relation to the arbitrary zero point, the centroid of the two component fit to the geocoronal line is located at 96.8 km/sec in this figure and its intensity is 4.1 Rayleighs. The fit in Figure 1 also includes the galactic emission (.20 R) at 105 km/sec and a faint atmospheric emission (0.13 R) at 57.5 km/sec [Nossal et al., 2004; Hausen et al., 2002].
Figure 8: Balmer $\alpha$ intensities for the entire PBO data set as a function of shadow altitude (km). *upper image*: evening and morning intensity data combined. *lower images*: intensity data separated into pre- and post-midnight sets (i.e., “pm” and “am” data). Low shadow altitude intensities for the morning exosphere are typically 20% brighter than evening intensities for the same viewing geometry. (*Plotting symbols*: ◦’s correspond to OZA $\leq 15^\circ$, □’s correspond to $15^\circ <$ OZA $\leq 30^\circ$, and △’s corresponds to $30^\circ <$ OZA $\leq 45^\circ$.)
Figure 9: Doppler widths for the entire PBO data set as a function of shadow altitude (km), where $|\text{VLSR}| \geq 10$ km/s.  
*upper image:* evening and morning Doppler width data combined.  
*lower images:* Doppler width data separated into pre- and post-midnight sets (i.e., “pm” and “am” data).  
A persistent narrowing of the profile with shadow altitude is apparent in the majority of the PBO data; a decrease of $\sim 500$ K in terms of effective temperature, from $\sim 850$ K near 500 km to $\sim 350$ K near 20,000 km.  
(*Plotting symbols:* $\bigtriangleup$’s correspond to $\text{OZA} \leq 15^\circ$, $\boxplus$’s correspond to $15^\circ < \text{OZA} \leq 30^\circ$, and $\bigtriangleup$’s corresponds to $30^\circ < \text{OZA} \leq 45^\circ$.)
Figure 10: Lyao rt model (a-c) and 03-03-00 PBO (d) Balmer α Doppler widths vs. shadow altitude (km). Lyao rt accounts for contributions to the emission from both multiple (dotted lines in (a-c)) and single scattering (solid lines in (a-c)). Lyao rt model Doppler widths were evaluated for each observation line of sight in the 03-03-00 PBO data set; Plotting symbols: ◆’s correspond to OZA ≤ 15°, □’s correspond to 15° < OZA ≤ 30°, and △’s corresponds to 30° < OZA ≤ 45°. In model run (a) an isothermal exosphere was used. Model runs (b) and (c) employed a nonisothermal exosphere. Φ = 3 × 10^8 cm⁻² s⁻¹ in model run (b) and Φ = 1 × 10^8 cm⁻² s⁻¹ for run (c). (Plotting symbols: ◆’s correspond to OZA ≤ 15°, □’s correspond to 15° < OZA ≤ 30°, and △’s corresponds to 30° < OZA ≤ 45°.)
Figure 11: Hydrogen diffusive flow profiles for the sample lyao_rt model runs in Figure 10, with $\Phi = 1 \times 10^8$ cm$^{-2}$ s$^{-1}$ and $\Phi = 3 \times 10^8$ cm$^{-2}$ s$^{-1}$. The corresponding MSIS temperature profile is also included.

Figure 12: (a) Percent cascade contribution to the total Balmer $\alpha$ intensity vs. shadow altitude (km). Two limits were used to restrict the full PBO data set (Figure 8) in order to achieve an accurate cascade determination: VLSR $< -10$ km/s or VLSR $> 35$ km/s, and a pointing direction at least $\pm 60^\circ$ in galactic latitude (i.e., well out of the galactic plane). The PBO data set indicates a cascade contribution at Balmer $\alpha$ of $\sim 5\%$. 
Figure 13: (a-b) Geocoronal Balmer $\alpha$ with small galactic contributions. The arrows indicate the position of the LSR at the time of the observations; 25 km/s to the red of the geocoronal line in (a) and -25 km/s to the blue of the geocoronal line in (b). As galactic Balmer $\alpha$ is rather broad ($\sim$25 km/s), even when significantly Doppler shifted from the geocoronal line center, galactic contributions from the wings of the galactic emission may overlap the geocoronal profile and be mistakenly fit as geocoronal emission. In Figure 13a galactic contributions may be mistaken as cascade emission. In Figure 13b galactic contributions are unlikely to affect cascade determination; determination of the geocoronal line width may, however, be affected by the galactic contamination. ($Abscissa$: bin number, where 1 bin = 0.75 km/s; bin 0 corresponds to the central sample bin, hence wavelength decreases from left to right.)
Figure 14: WHaM Balmer \( \alpha \) and Balmer \( \beta \). Representative Balmer \( \alpha \) (upper curve) and Balmer \( \beta \) (lower curve) intensities vs. time (local and UT), as measured with WHaM on 05-24-01. Alternating “blocks” Balmer \( \alpha \) and Balmer \( \beta \) observations were conducted with 30 s and 60 s integration times respectively. The annular summing technique has made this kind of observation possible for the first time. All observations are within 10° of the zenith.
Figure 15: Examples of candidate solutions from the data–model comparison search by Bishop et al. [2004]. Forward modeling fits are to Fabry-Perot data from the Pine Bluff Observatory and to EURD Satellite Lyman α data using global resonance radiative transfer modeling.
Figure 16: Fabry-Perot observations of geocoronal Hα emissions observed over solar cycle 22 from Wisconsin. The emission intensity was ratioed to the *Anderson et al.* radiative transfer solar maximum submodel predictions to facilitate comparison of data taken in different viewing geometries. Each point on this graph represents a bin containing multiple nights of observations.
Figure 17: Upper atmospheric Hα column emission intensities at 2000-km shadow altitude plotted versus day number for the year 1997. Viewing geometry variations likely account for most of the apparent scatter.
Figure 18: Solar Cycle 23 WHAM thermospheric + exospheric Hα column emission intensity observations taken between December and the Spring equinox and in observing directions pointed toward low galactic emission [less than 0.25 R at Hα] regions of the sky. The solar minimum (F10.7 69-76) data are from 10 nights of observations, the solar medium data (F10.7 100-122) are from 5 nights of observations and the near solar maximum data (F10.7 134-163) are from 8 nights of observations.
Figure 19: $\text{H}\alpha$ column emission observations from the WHAM Fabry-Perot at the Kitt Peak, Az Observatory and from the Pine Bluff, WI Observatory taken during the same dark of the moon period in February, 2000.
### Table 1: Balmer α emission components.

<table>
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<th>Component</th>
<th>Transition</th>
<th>(\sigma) (cm(^{-1})) *</th>
<th>(\lambda_{air}) (Å) †</th>
<th>(\Delta v) (km/s) ‡</th>
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\* vacuum wave numbers from Garcia and Mack [1965]

\(\lambda_{air} = \lambda_{vac}/\mu\), where \(\mu = 1.0002762\) at Balmer α

\(\Delta v\) velocity intervals are referenced to component 4

### Table 2: Lyao rt model inputs, “pm” and “am” exospheres.

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10 References


