COMOSPHERIC WAVES

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Figure 1. The 1 m Fourier transform spectrometer (FTS).

ABSTRACT

The puzzling cool “COMosphere” is an important interface between the radiatively controlled outer photosphere and the dynamics-dominated chromosphere. High-resolution spectroscopy of the thermal infrared rovibrational bands of carbon monoxide is a key tool to elucidate the physical properties of the cool gas, and to search for dynamical signatures of the waves that shock at higher altitudes to excite the Ca II “K grains” and other phenomena. An adaptive optics system developed for the McMath-Pierce telescope has shown exceptional promise for improving thermal infrared observations, particularly with the very high-resolution Fourier transform spectrometer. At the same time, AO and integral field units now are allowing high-quality imaging spectroscopy (albeit at lower spectral resolution) of the CO lines over 10⁶ x 10⁶ areas with high enough cadence to measure the wave field down to periods of about 10 s.

Key words: carbon monoxide; infrared spectra.

1. INTRODUCTION

The COMosphere is a cool layer (T ~ 3500 K) thought to extend from the upper photosphere several hundred kilometers into what usually is thought of as the warm middle chromosphere (T ~ 7000 K). The main observational signatures of the COMosphere are the anomalous limb darkening of the strong 5 μm rovibrational bands of carbon monoxide, and the curious off-limb emissions of the same species. The origin, spatial pervasiveness, and physical significance of the region have been hotly debated over the past several years (see Ayres 2002, and references to previous work therein). Although the nature of the COMosphere remains to be settled, one thing is clear: at disk center, the strong CO lines achieve τ ~ 1 in the high photosphere, and thus are sensitive to the wave energy propagating up through that region, ultimately into the chromospheric “canopy” above (see Ayres & Braula 1990). The infrared studies of waves in the high photosphere thus provide an important boundary condition for the dynamical fine structure seen at higher altitudes in the ultraviolet by SOHO and TRACE.

2. SOLAR INFRARED INSTRUMENTS

In this presentation, I will describe some of the recent advances in infrared observing techniques at the McMath-Pierce telescope on Kitt Peak, operated by the National Solar Observatory. Although the facility was constructed some 40 years ago, it still remains, at 1.5 m, the largest solar telescope in the world. That, and its all-reflecting design are crucial for thermal infrared work. The McMath-Pierce main beam is diffraction limited at 0.8," which is comparable to the seeing experienced under good observing conditions during the early morning hours on the Peak.

There are two major instruments at the McMath-Pierce that are used for thermal IR spectroscopy. The first is the venerable Fourier transform spectrometer (FTS: Braula 1978), shown in Fig. 1, which was prized in the exploration of the CO 5 μm rovibrational bands in the late-70’s and early-80’s because it can be operated at extremely high resolution (ω/Δω ~ 2 x 10⁶ at the ω = 2145 cm⁻¹ CO bands), it has an exceptionally clean instrumental profile, and can capture large stretches of the spectrum in a single observation (see Ayres & Testerman 1981). The two former characteristics are important for recording accurate lineshapes of the CO absorption features: the core depths, in particular, of these narrow LTE lines map


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almost directly the temperatures at the depths where the cores become optically thick. Lower resolution and/or scattered light (e.g., from grating ghosts in a conventional dispersive spectrometer) can fill in the line cores, leading to overestimates of the $\tau = 1$ temperatures; a minimum resolution of $\sim 1.2 \times 10^6$ is required to fully resolve the sharp CO features near disk center. The broad spectral coverage in a single observation can take advantage of the unique highly redundant nature of the extensive widely dispersed 5 $\mu$m CO bands, in the face of atmospheric absorption which affects that entire wavelength region. The major disadvantages of the FTS are: (1) even the fastest scanning mode requires about 40 s, which hinders studies of short-period phenomena like 3-minute chromospheric waves, and prevents observations at the limb owing to the possibility of rapid changes in illumination due to image shake; and (2) only a single spatially integrated area can be observed with the current single channel detector system.

The other major IR instrument at the McMath-Pierce is the InfraRed Imaging Spectrometer (IRIS; see Ayres & Rabin 1996, and references therein), shown in Fig. 2. It is based on the 14 m vertical spectrograph (the upper 1 m of which is visible in the figure), which Keith Pierce modified in the early 1990’s to carry a large infrared grating scavenged from a horizontal IR spectrograph built by Don Hall two decades earlier (but later abandoned for safety reasons). IRIS also makes use of the IR camera system developed by Doug Rabin as part of his Near-Infrared Magnetograph (NIM). The camera is a relatively primitive Amber Engineering 256x256 InSb chip, which is cooled to about 40$^\circ$ K using solid N$_2$. (The dewar is the gold chamber seen in the middle of Fig. 2). A major current initiative at NSO involves replacing that camera with an astronomical-quality Aladdin array from the National Optical Astronomy Observatories.

The combination of the vertical spectrograph and the AE camera should yield in theory a resolving power of $\sim 10^6$, but in practice one obtains only about half that due to scattering wings on the instrumental profile. Disappointing as the resolution is, IRIS does have the important advantage of long-slit 1-D spatial imaging ($\sim 50''$ along the slit) at high cadence (about 20 frames per minute) with short exposures (0.5 s, or less) that are less susceptible to seeing effects than the FTS. Although the low spectral resolution is unsuitable for absolute thermal imaging, it is adequate for measuring relative temperature and velocity changes: from point-to-point on the surface, or over time during the passage of a wave disturbance.

Short exposures combined with the long-slit imaging also are valuable for recording the off-limb emissions of CO, as illustrated in Fig. 3. The dark cores of the two CO lines visible in the image at lower left continue above the limb (still at the low brightness temperature of 3600 K, or less), while the photospheric continuum fades rapidly into the dark background sky. A surface plot of the translimb spectrum of the region is shown in the upper middle: red and blue intensity tracings correspond to the continuum and line core spatial profiles depicted in the chart to the right. The CO off-limb extensions are less than an arcsecond, actually comparable to the diffraction limit of the telescope, but are measured to much higher accuracy as

![Figure 2. InfraRed Imaging Spectrometer (IRIS) on the 1.5 m McMath-Pierce solar telescope at Kitt Peak.](image)

![Figure 3. Off-limb emissions of CO recorded by IRIS.](image)
Figure 4. Fast tip/tilt system installed at front end of FTS. Bright circle (middle left) is an initial fold flat that feeds the collimator (leftmost of the two dark squares). Parallel light from the collimator falls on the tip/tilt mirror, the small circle to upper left of the image splitter (white square in center right), which returns the corrected beam to the camera mirror (rightmost dark square). The latter feeds 1% of the light to the fast CCD camera (in back, upper right) via the image splitter, to close the servo loop; and the rest of the corrected image is sent to the FTS (to right of picture).

a differential effect. Here, the fact that the detector provides a very stable relative height scale for the intensities during a single short exposure is absolutely essential for measuring the rather subtle effect. It should be said, however, that the phenomenon originally was discovered by NSO staff scientist Bill Livingston back in the early 1990’s using a single-channel scanning version of IRIS, and stepping the spectrograph slit sequentially across the limb. This setup should not have been able to observe the CO off-limb emissions, but nevertheless was successful; due to the skill of the observer and the excellent conditions during that particular morning (see Solanki, Livingston, & Ayres 1994).

3. NEW ADVANCES

Recently, two major advances have occurred that promise to revolutionize thermal IR CO work, particularly with respect to studies of dynamics in the high photosphere. First was the development by Christoph Keller and Claude Plymate in 2002 of a fast tip/tilt image motion compensator, which this year (2003) evolved into a full-up Adaptive Optics system. The second important development was the resurrection of a set of all-reflecting Bowen-style image slicers, which originally had been fabricated under the direction of Keith Pierce in the mid-1960’s for integral field spectroscopy, but never used extensively then owing to lack of large format digital imaging systems. I will describe early results from three separate experiments that utilized different combinations of these two advances, and which are relevant to the thermal structure of the outer photosphere and its wave field.

4. EXTREME-LIMB AND TRANSLIMB CO SPECTROSCOPY WITH THE FTS

Fig. 4 illustrates the original fast tip/tilt system, which Claude Plymate and I used in April and August 2002 with the FTS in an effort to record high-quality CO spectra very close to the solar limb, and even across it. Observing close to the limb probes the highest altitudes in the upper photosphere and low chromosphere accessible to optically thick lines in the strong CO $5 \mu$m bands. The hope was that the tip/tilt system would compensate for most of the image jitter at limb, using the sharp edge of the disk as a strong servo fiducial, and thereby stabilize the illumination through the narrow FTS aperture during the long interferogram scan (requiring about 4 minutes in the mode we were using). During the April run, we took advantage of good observing conditions—decent seeing and moderate breeze—to record high spectral resolution scans as close as $\mu = 0.076$ to the IR continuum limb ($1.17$ mm $\sim 2.8$ inside the limb). The most reliable previous FTS limb spectra of CO were taken at $\mu = 0.20$ ($8.2$ mm $\sim 19''$). The intensity tracings were accurately calibrated to theoretical continuum models, and are illustrated in Fig. 5 (the uppermost red curve is a reference disk center [$\mu = 1$] spectrum derived from several taken during the sequence: telluric absorption has been removed from each tracing). The strongest CO lines at disk center have core brightness temperatures of about $4300$ K, somewhat cooler than the $T_{\text{min}}$ of $1$-D solar reference models like the VAL C$^\text{r}$, but the line centers darken to nearly $3500$ K at the extreme limb, comparable to $T_{\text{min}}$ in some modern models of cold sunspots (e.g., Umbral Core model L of Maltby et al. 1986).

In August of that year, we again set up the fast tip/tilt system on the FTS, and this time attempted to scan across the limb. We were fortunate to have an exceptional day of good seeing and very light wind, and were able to run the FTS in a special fast-scanning mode that required only $40$ s per interferogram. A surface plot of a small portion of our translimb scans is illustrated in the lower part of Fig. 6, and compared in the upper part with one of the best IRIS spectra we have (dark dot-dashed). The tip/tilt system apparently maintained a very stable geometrical
reference for the individual scans, and the higher quality of the FTS data in S/N and resolution compared with IRIS is evident. We are hopeful that detailed 2-D thermal modeling of the FTS translimb profiles will help dissect the physical structure of the outer solar photosphere where these strong CO lines arise (see, e.g., Ayres 2002).

5. THE NEW ERA OF ADAPTIVE OPTICS ON IRIS

This year (2003), Claude Plymate and I have carried out a number of experiments on IRIS initially with the fast tip/tilt system and conventional long-slit imaging, but later with the full-up AO compensation and an integral field unit (IFU) based on a 4mm×4mm Bowen-style image slicer. I’ll describe examples of each application.

5.1. Drift Scanning at the Limb

In March 2003, we operated near the west limb (the McMath-Pierce, because the heliostat underfills the primary mirror, has its best spatial resolution in the E/W direction) with the fast tip/tilt system, running the 50″ slit radially, extending about 10″ above the limb. We turned off the tank rotation (which compensates for the diurnal rotation of the image), thereby allowing the image to drift past the slit at a rate of about 4″ per minute. We snapped off AE frames at about 20 per minute, thereby oversampling the spatial resolution tangent to the limb by a factor of 5. We selected the best frame (or frames) for each spatial bin along the limb according to a limb-sharpness criterion, and assembled them into the image depicted in Fig. 7. What is shown is a continuum image on the left (which doesn’t display much structure) and a CO line-core map on the right, which displays a significant amount of structure: the lighter bandings very likely are network lanes seen in projection; these show up as CO bright points near disk center (e.g., Ayres & Rabin 1996). But, very close to the limb, the apparent structure in CO smoothes out and the limb itself is relatively featureless. This probably is due to “shadowing” by cool upper-altitude CO, which eventually blocks the view of thermal inhomogeneities beyond the $\tau = 1$ horizon along the highly inclined sightline.

5.2. Slicing up the Sun

A few months later, in June 2003, Claude and I experimented with one of the Pierce image slicers mentioned previously. At the same time, Keller and Plymate had perfected their infrared AO system (Fig. 8). The IFU allows a 10″×10″ area on the Sun to be spectrally imaged in a single exposure with the existing AE camera, while the AO system mitigates atmospheric blurring. The sharpest frames are selected after the fact, and assembled into a 2-D spatial time series of CO parameters: line core temperatures, widths, and Doppler shifts.
The 4mm×4mm slicer is illustrated in Fig. 9, and the cleverly designed (see Pierce 1965) stack of glass plates at its heart in Fig. 10. The device lays down a sequence of slit subimages, each about 10′ tall, along the spectrograph entrance slit with small gaps between each slice. Fig. 11 illustrates a flat-fielded and geometrically corrected AE image with four of the ten possible slices fully on the detector. The vertical dark stripes are the CO lines in each segment (from the same region illustrated in Fig. 5), while the horizontal dark bands represent the narrow gaps between the slices.

We used the four-slice configuration to observe at the limb, because the spatial sampling in the slit direction (about 5 pixels per arcsecond) is optimum for recording the off-limb CO emissions. Otherwise, on the disk, we used a “magnifying” lens in the camera transfer optics to permit as many as eight discrete slices to be recorded at one time, thereby maximizing the spatial coverage perpendicular to the slit (one slice corresponds to about 1′′). The spatial sampling along the slits on the disk, 2.5 pixels per arcsecond, is close to Nyquist for the best resolution (∼ 1′′) we obtain with AO under good observing conditions.

We have had only a few runs with this setup, and still are gaining experience with it. In fact, our first run in June 2003 has proved to be the best so far in terms of good observing conditions. Fig. 12 illustrates a time sequence...
obtained with a small sunspot centered in the AO field of view, and the slicer aperture offset to one corner (as far into "quiet Sun" as possible but still achieving a good AO correction). Each frame is a time sequence for one of six slices that were recorded during the observation (two additional slices were on the camera, but the quality was poorer owing to vignetting). The unaltered continuum is shown in the left column, and a CO line core map in the right column. The "fading" of the continuum signal in the top three panels is due to clipping the edge of the sunspot's penumbra. The CO map was divided by the (largely featureless) continuum distribution to remove any illumination changes due to, for example, seeing or light cirrus.

Careful examination of the CO maps shows oscillatory intensity changes over most of the length of the slit, and coherent over several of the slices. These undoubtedly are p-mode wavepackets, like those seen in other imaging efforts that utilized a raster-scanned slit to build up spatial coverage. The advantage of the IFU here is that the field of view is contiguous, large enough to contain an entire p-mode wavepacket, and can be imaged altogether in the time required to expose and store a single frame (seconds). This offers the possibility to study much shorter wave periods than have been accessible in the past, and we hope in future observing runs to exploit this advantage for studies of the wave fields that ultimately give rise to the K bright grains at higher altitudes.

6. FOR THE FUTURE

As Mats Carlsson and Bob Stein have pointed out, waves indeed might be responsible for the very existence of the COmosphere itself (see Carlsson & Stein 1995). On the other hand, the presence of CO cooling in the outer atmosphere might significantly damp these waves above the classical $T_{\text{min}}$ and postpone the formation of the K grains to higher altitudes. Either way, the response of the CO 5 $\mu$m spectrum is an important diagnostic for wave phenomena high in the solar atmosphere, complementary to ultraviolet line and continuum emissions that form in higher layers.

All in all, the current advances on the venerable 40-year old McMath-Pierce telescope are in many respects simply pathfinding for the true revolution in infrared solar spectroscopy anticipated for the end of this decade: the commissioning of the Advanced Technology Solar Telescope. ATST will be a 4 m behemoth (at least relatively speaking in the solar world) at an excellent site, and outfitted with the next generation imaging spectrometers, in the visible as well as infrared. This facility will finally allow us to resolve many of the outstanding controversies in contemporary solar physics, not the least being the origin of the COmosphere, and the role it plays, if any, in modifying the transport of energy through the outer photosphere into the mechanically heated "magnetic transition zone" above.

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REFERENCES