LIMB OBSERVATIONS OF THE 12.32 MICRON SOLAR EMISSION LINE
DURING THE 1991 JULY TOTAL ECLIPSE

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ABSTRACT

We determined the limb profile of the Mg I 12.32 μm emission line by occultation in the 1991 July 11 total solar eclipse over Mauna Kea. The observations used the NASA 3 m Infrared Telescope Facility and a new Goddard large cryogenic grating spectrometer. The results show that the emission peaks very close to the 12 μm continuum limb, as predicted by recent theory for this line as a non–LTE photospheric emission feature. However, the increase in optical depth for this extreme limb-viewing situation means that most of the observed emission arises from above the chromospheric temperature minimum, and we find that this emission is extended to heights well in excess of the model predictions. The line emission can be observed as high as 2000 km above the 12 μm continuum limb, whereas theory predicts it to remain observable no higher than ~500 km above the continuum limb. The substantial limb extension observed in this line is qualitatively consistent with limb extensions seen by other observers in the far-IR continuum, and we conclude that it is indicative of departures from gravitational hydrostatic equilibrium, or spatial inhomogeneities, in the upper solar atmosphere.

Subject headings: infrared: general — Sun: atmosphere — Sun: general

1. INTRODUCTION

The 12 μm emission lines are the most Zeeman-sensitive lines that are currently observable in the solar spectrum, and they have substantial applications to solar and stellar magnetic and electric field studies (Deming et al. 1988; Chang & Schoenfeld 1991). When the lines were initially observed by Braut & Noyes (1983), it was believed that they originated in the low solar chromosphere. Early attempts to model the line formation process (Lemke & Holweger 1987) suggested that these emission features are more likely to be photospheric than chromospheric in origin. Although Zirin & Popp (1989) argued for chromospheric formation, recent theoretical work by several independent groups (Hoang-Binh 1991; Chang et al. 1991; Carlsson, Rutten, & Shchukina 1991, hereafter CRS) has produced a consensus that the lines are formed by departures from local thermodynamic equilibrium (LTE) in the upper photosphere. In particular, CRS obtain excellent agreement with the observed line profiles, from an essentially ab initio calculation, without adjustable parameters. Observations of the strongest line (Mg I 12.32 μm) provide indirect evidence for formation near the temperature minimum region (Deming et al. 1988), consistent with the recent theory. However, it remains desirable to show that the line is photospheric via direct observation of the height of the emitting layer at the limb. Such observations are facilitated by the substantial limb brightening of the emission (Braut & Noyes 1983) but are hampered by the diffraction-limited spatial resolution attainable with existing solar telescopes at 12 μm. One solution to the problem of spatial resolution is to observe the line intensity during an eclipse, exploiting the motion of the lunar limb to obtain very high spatial resolution observations. In this Letter we present observations of the height of the 12.32 μm line emission at the solar limb, obtained using slitless IR spectroscopy of the limb during the 1991 July 11 total eclipse.

2. OBSERVATIONS

We observed the 12.32 μm line at the solar limb using the 3 m NASA Infrared Telescope Facility (IRTF) on Mauna Kea. The observations used a new high-resolution cryogenic grating spectrometer developed at Goddard for planetary and astrophysical applications (Jennings et al. 1992). This Cassegrain instrument, which we refer to as Celeste, utilizes a 15 × 30 cm grating in a Littrow configuration, and is designed for multiple-pass operation in the 5–20 μm spectral range. For these observations the 31.6 line mm⁻¹ grating was illuminated by a 12.5 cm diameter beam in fourth order, giving a diffraction-limited single-pass spectral resolution of 0.03 cm⁻¹. The grating, and all other internal optics, were cooled with liquid helium to approximately 6 K, resulting in a very low thermal background noise level. Observations were planned for both second and third contact, with telescope motions directed by the data acquisition (386) computer. Unfortunately, the telescope motion to the third contact limb did not occur, because of a communication failure between the data computer and the telescope control system. However, excellent data were obtained at the second contact (east) limb.

Allowing for the possibility of instrumental malfunctions, we began preparing Celeste for use approximately 1 week before the eclipse. However, problems with the 10 × 50 array of blocked impurity band (BIB) detectors were not solved until approximately 6 hours before the eclipse. During resolution of the array problems, it became necessary to cut the feed-

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through which adjusts the focus of the cold optics externally. The internal focus was set to a nominal value based on prior experience in the laboratory. Since the eclipse was an early morning event, we had only 45 minutes available from the acquisition of the Sun above the edge of the dome until second contact at 7:28 a.m. local time. To save time, we elected to use a telescope focus value which was estimated from the IRTF documentation and the measured position of the Celeste entrance aperture. This left only two adjustments to be made using sunlight: positioning the telescope at the extreme solar limb, and adjusting the grating angle to center the emission line on the detector array. The line was found and centered by first setting the grating to the approximate position of the line, and viewing the array detector output while slowly scanning the grating. The array output was shown as a false-color display, and limb brightening of the line was verified by moving the telescope from the limb to a position well on the disk. The resultant grating angle agreed exactly with a prior calibration made using an NH$_3$ gas absorption cell in the laboratory at GSFC. A cold entrance slit was used in Celeste during the line centering and limb positioning, but was removed for the eclipse.

The 3 m telescope aperture was covered with white polypropylene plastic, of a variety used in the food packaging industry. The polypropylene scattered the visible and near-IR radiation to a sufficient degree to prevent damage to the telescope, and Celeste optics, from focused visible sunlight. However, at 12 μm the polypropylene scattering was much reduced, allowing a definable limb to be observed for the purpose of line selection and limb positioning. The polypropylene was removed ~40 s before second contact. We observed the second contact limb at the celestial easternmost point of the disk. This point was found by moving east along the bisector of a north-south chord, and we estimate that the uncertainty in the limb positioning is ~5" in the north-south direction and ~2" east-west.

A variety of cold entrance apertures are selectable in Celeste. We elected to use a slitless mode for the actual observations, choosing a rectangular focal-plane aperture which projected to 6" × 20" on the sky. The long axis of the aperture was parallel to, and centered on, the 6" × 30" projected extent of the detector array. We oriented the aperture and array with their long axis perpendicular to the solar limb, and the spectral dispersion was along the long (50-pixel) axis of the array. The rationale for slitless operation was to maximize the signal-to-noise ratio by eliminating the losses which occur using an entrance slit, and possibly to sample more than a single location along the limb (this latter advantage was not realized in practice). Our concern about the signal-to-noise ratio reflects the fact that the solar intensity is much reduced in the 12 μm region as compared with the visible, and high temporal and spatial resolution was needed. The observations consisted of a sequence of 150 consecutive measurements, each consisting of 0.2 s integration plus 0.12 s of overhead. Each integration was the result of co-adding approximately 50 frames of the array, which was read at 250 Hz, the maximum rate possible. The necessity for rapid reading and co-adding was to minimize saturation of the array electron wells by the large solar continuum signal. Since the lunar limb motion was 0.53 s$^{-1}$, the spatial resolution of a single integration could be as high as 0.15. No sky chopping was used. After second contact, the thermal background level on the Moon was measured at the center of the lunar disk, and after third contact flat-field calibration of the array response was performed. The flat-field calibrations were performed by illuminating the Celeste entrance aperture using a variety of extended warm sources, such as the inside of the dome, an experimenter’s hand, the shaft of a soldering iron, etc. The inside of the dome was observed using the telescope, but the other sources were inserted into an opening between the Celeste entrance aperture and the telescope Cassegrain mounting plate.

3. DATA ANALYSIS

Reduction of the data consisted of a subtraction of the lunar background emission (a small contribution) and division by a flat-field calibration. Inspection of the flat-field data reveals that the line emission is about an order of magnitude broader than the expected 0.03 cm$^{-1}$ diffraction-limited resolution. Moreover, all of the 10 rows of the array give essentially identical results for the timing of the line and continuum disappearance, consistent with a spatial resolution not much better than the 6" extent of the array. We cannot unequivocally specify the source of the lower-than-expected spatial and spectral resolution. However, a number of factors could contribute, such as imprecise focus of the telescope and in the Celeste internal optics, as well as aberrations which arise off-axis (the optical system was designed as a slit spectrometer, and off-axis effects are uncompensated).

In the data analysis we have used an average of the 10 array rows. The resulting data near second contact are illustrated in Figure 1, which shows the data in a three-dimensional form. The X-axis represents the column number of the array, which corresponds to wavelength, or to frequency in cm$^{-1}$ (0.02 cm$^{-1}$ per column). (The first two detector columns were not operational, so only 48 columns are illustrated.) The Y-axis represents time, and the Z-axis is average intensity over the 10 rows of the array. Successive integrations are shown by the

![Fig. 1.-Spectral data for the 12.32 μm line near second contact, in a three-dimensional representation. The X-axis is wavelength (increasing to the left; frequency increases to the right, with 0.02 cm$^{-1}$ per point), the Y-axis is time (equivalent to height in the solar atmosphere, 390 km per second of lunar limb motion), and the Z-axis is relative intensity.](image-url)
lines across the surface at 21 values along the Y-axis. The continuum radiation from the solar limb in the 1.0 cm\(^{-1}\) bandpass of the array was sufficient to saturate the BIB detectors until a few seconds before second contact. Figure 1 represents about 7 s of data, corresponding to only a few arcseconds of lunar limb motion. The portion of the data near the X-axis origin is representative of the 12 \(\mu\)m continuum, which drops rapidly to zero at second contact. The emission line is the "ridge" structure located near the largest X-values in the figure (peaking near col. [38]); it can be observed for up to 5 s following the disappearance of the continuum. Its X-position in Figure 1 corresponds to the position of the limb in the slitless aperture.

Because the intrinsic line width (0.02 cm\(^{-1}\)) is not spectrally resolved by our measurements (0.3 cm\(^{-1}\) resolution), all of our data and discussion refer only to the total energy integrated over the line profile, not to intensities at specific wavelengths. The wavelength-integrated line signal, and the continuum signal, are shown as a function of time in Figure 2. The line signal was derived by subtracting a continuum contribution from the total flat-fielded array signal (i.e., the sum of cols. [3]–[50]). The continuum contribution was calculated by taking column (3) of the flat-fielded array (the farthest left point in Fig. 1) as representative of the continuum level, and assuming it to be constant with wavelength. We made no attempt to correct for the fraction of line emission which misses the array on the right. Since the relevant data span only a few seconds of time, the line position does not shift appreciably on the array, and the relative shape of the limb emission profile is unaffected by the fraction of the total line intensity which is missed. The line and continuum data in Figure 2 are plotted on different relative intensity scales; the intensity scale for the line energy is expanded by a factor of 10 from the continuum scale. Also illustrated in Figure 2 is a simulation of the total line energy expected versus time, based on the CRS theory.

The data in Figures 1 and 2 represent the total signal from regions not covered by the lunar limb. Hence, extraction of high spatial resolution information requires that successive measurements be differenced. If the position of the lunar limb is the only factor which changes between successive observations, then the differenced data will represent a high spatial resolution scan of the solar limb. The differenced series for our data are shown in Figure 3 for both the line and the continuum signals. The height in Figure 3 is defined to be zero at the 12 \(\mu\)m continuum limb; the visible continuum limb is at \(-400\) km on this scale (Chang et al. 1991). Since the transmission of the terrestrial atmosphere is not precisely constant between successive integrations, noise is present in the total signals (Fig. 2), and becomes more evident in the differenced data (Fig. 3). The noise on the total (line + continuum, undifferenced) signal can be estimated by the departures of individual values from a smooth (e.g., linear) temporal variation; these fluctuations are typically 3% of the total signal and occur primarily on a "slow" time scale (typical one to several seconds). Before second contact, when the total signal is largest, its noise fluctuations can result in prohibitively large errors in the differenced line signal. We therefore only plot emission points according to the criterion that the differenced line signal must be larger than a 3% fluctuation in the total signal. This rather conservative prescription limits us to consideration of points at and above the continuum limb (Fig. 3). For the points illustrated, the error bars were calculated by assuming that the emission is itself affected by 3% sky-transparency fluctuations, as well as by statistical fluctuations in the thermal background emission. Near the limb, the error bars exceed the fluctuations in the observed points, which is probably due to the fact that the differencing removes much of the relatively slow transparency fluctuations. Well above the limb the error bars are dominated by statistical background fluctuations, and the fact that the observations show scatter in excess of the errors indicates either that real structure is being observed or that an unaccounted-for source of error exists.

Since the lunar limb is irregular, our 6\(^\circ\) resolution parallel to the limb causes the perpendicular resolution to be degraded by an amount corresponding to the range of heights present in the observed portion of the lunar topography. We calculated the maximum extent of this degradation using the charts of Watts (1963), and including libration for the summit of Mauna Kea. The relevant lunar topography has a range of heights which typically extends to 0.3 over 6\(^\circ\) of the limb. We therefore
assume that our height resolution of the solar atmosphere is about 220 km, and this is consistent with the appearance of the 12 μm continuum limb in Figure 3.

We have calculated the theoretical limb profile of the emission using the CRS theory and accounting for the sphericity of the emitting layers at the extreme limb. CRS do not give the emission source function to sufficiently small optical depths for this purpose, so we extended their model by reference to the Chang et al. (1991) calculations, which do not reproduce the observed spectral line profiles as well but extend to smaller optical depths. Specifically, we adopted the CRS model, extrapolating their line source function to smaller optical depths by assuming that, at line center, \( d \log S/d \log \tau = -0.128 \), taking this gradient from Figure 1 of Chang et al. (1991). The line profile for these calculations was assumed to be Gaussian, with a FWHM of 0.017 cm\(^{-1}\). Because our observations refer to the total energy in the line, we summed the computed intensity over frequency in the line. We convolved the resultant limb emission profile with a rectangular function of 220 km width, to simulate the degradation due to lunar topography. The resultant profile is shown as a dashed line in Figure 3, and the dashed line in Figure 2 represents its integral over height.

4. RESULTS AND DISCUSSION

Figure 3 shows that the observed emission profile peaks very close to the 12 μm continuum limb, as predicted by theory for a non-LTE emission line. The emission peak is not displaced by the approximately 700 km which would be required for an LTE chromospheric emission (Chang et al. 1991). On the other hand, the peak in the emission is not nearly as distinct as predicted by the CRS theory, and the emission extends much higher than was calculated from the theory. Using the continuum as a reference, it is possible to compare the magnitude of the observed line energy with theory. The observed line intensity scale in Figure 3 has been expanded by a factor of 10 relative to the continuum scale. Recalling that the continuum refers to the total energy in the 1.0 cm\(^{-1}\) bandpass of the array, we see that the observed peak line energy is about 0.7/10 = 7% of the continuum signal, i.e., equal to the energy in 0.07 cm\(^{-1}\) of the continuum. Our calculations using the CRS line source function indicate that the line-core–to-continuum specific intensity ratio is ≈2 just inside the limb, but optical thickness makes the total line energy depend on the form adopted for the line profile. Using a Gaussian profile of 0.017 cm\(^{-1}\) FWHM, we can account for only one-third of the observed line energy. However, more realistic profiles, which allow for significant opacity in the line wings, will give greater values for the calculated line energy. Since we lack a spectrally resolved observed line profile for this extreme limb geometry, we cannot resolve this issue, and the theoretical curves in Figures 2 and 3 have not been normalized to any particular absolute value; only their shape is significant. However, observations on the disk (e.g., Brautl & Noyes 1983) imply that the total line energy above the limb cannot greatly exceed the theoretical prediction. Our observed extension to greater heights therefore does not necessarily imply that extra emission is present, only that the scale height of the emitting layer is several times greater than in the model.

The good agreement which CRS obtain for the observed profiles of the line at \( \mu = 1.0 \) and 0.2 shows that their model correctly predicts the dependence of the source function on optical depth, \( S(\tau) \). However, the height dependence of the emission source function, \( S(h) \), is not constrained by such comparisons, and the heights from the model are computed under the assumption that the solar atmosphere is in gravitational hydrostatic equilibrium (e.g., Vernazza, Avrett, & Loeser 1981, hereafter VAL). Specification of \( S(h) \) is critical to proper interpretation of magnetic data taken in the 12.32 μm line and is preferentially derived by direct observation. Eclipse observations in the far-IR continuum have shown that the limb is extended to heights well above the predictions of the VAL model. Lindsey et al. (1986) found that the 100 and 200 μm continuum limbs were extended by ~1° above the VAL prediction, implying "large departures from gravitational-hydrostatic equilibrium almost immediately above the chromospheric temperature minimum." Although the 12.32 μm line is photospheric when seen on the disk, the increase in optical depth for the extreme limb-viewing situation means that most of the emission observed here arises from above \( T_{\text{meq}} \), where such departures occur. However, the Lindsey et al. (1986) results require substantial enhancements in chromospheric density, and it is not clear what effect such enhancements will have on the 12.32 μm emission. Also, spatial inhomogeneities surely exist at and above the temperature minimum. In a limb-viewing situation, inhomogeneities will have the effect of extending the observed emission to greater heights, and this effect is also a likely contributor to the extension which we observe. Models incorporating departures from hydrostatic equilibrium and spatial inhomogeneities will be required to understand fully the chromospheric portion of the 12.32 μm emission.

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