NEAR IR OBSERVATIONS OF THE 11 JULY 1991 TOTAL SOLAR ECLIPSE FROM MAUNA KEA, HAWAII

T. A. CLARK

Physics Department, University of Calgary, Calgary, Alberta T2N 1N4, Canada

D. A. NAYLOR and G. J. TOMPKINS

Department of Physics, University of Lethbridge, Lethbridge, Alberta T1K 3M4, Canada

and

C. LINDSEY

Solar Physics Research Corporation, 4720 Calle Desecada, Tucson, AZ 85718, U.S.A.

Abstract. Near IR total eclipse measurements have provided clear evidence during both 2nd and 3rd contacts for a limb extension of about 125 km for wavelengths in the range containing the CO fundamental vibration-rotation bands between 4.3 and 5.5 μm, when compared to the limb at nearby shorter wavelengths. This is interpreted as a "flash" spectrum in the CO lines, with the above extension representing the outer level of the CO emission layer. This height can be compared to the $\tau_{CO} = 1.0$ level incorporated into recent representative atmospheric models (Ayres and Wiedemann, 1989) which is 90 km above the visible limb for a semi-empirical "hot chromosphere" model (Avrett, 1985) and 220 km for a "cool" radiative equilibrium model based upon work by Anderson (1989).

Key words: CO molecule – eclipses – infrared: stars – Sun: chromosphere

1. Introduction

The vibration-rotation bands of CO in the near IR represent a valuable probe of the conditions in the atmospheres of the Sun and other cool stars (e.g. Ayres and Testerman, 1981; Heasley *et al.*, 1976). In the solar atmosphere, limb darkening of lines in these CO bands (Ayres and Testerman, 1981) and the line characteristics of low core brightness temperature and no central emission peak reinforced the conclusion of Noyes and Hall (1972), that the CO does not participate in the "normal" chromospheric heating. The upper photosphere and chromosphere appear to be bifurcated into a hot chromosphere ($T \sim 6000$ K) within the chromospheric network or above UV bright points and a cool ($T \sim 3500$ K) atmosphere above supergranular cells containing the majority of the CO gas (Ayres, 1990). Models of the solar atmosphere have been devised which incorporate both the CO cool regions and the hotter network from which the reversed cores of chromospheric lines arise and which include the expected height distribution of the CO emission. So far, no observation has measured this distribution at the limb.

The present measurement represents a preliminary attempt to determine the vertical extent of the CO layer by monitoring the intensity of the near IR spectrum between 2.8 and 5.4 μm including the fundamental CO V-R band, during the 11 July, 1991 total solar eclipse from Mauna Kea. This experiment was carried out as part of the visible eclipse monitoring in support of the international collaborative millimeter wave eclipse experiment on the 15-meter James Clerk Maxwell Telescope (Lindsey *et al.*, 1992).

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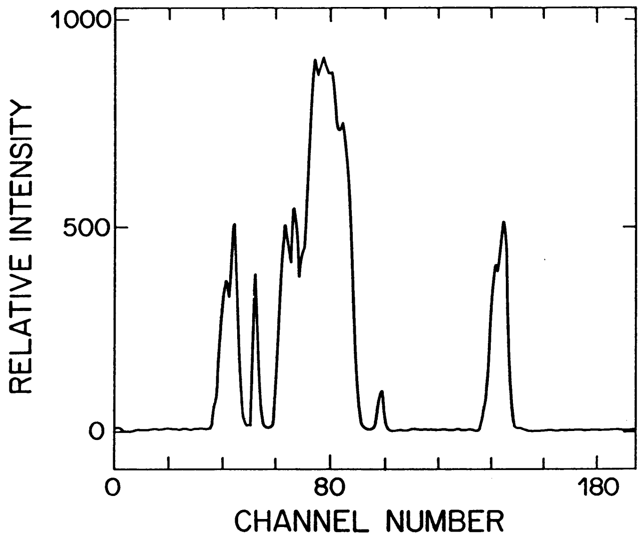

Fig. 1. Typical CVF spectrum of the Sun, taken during the eclipse.

2. Instrumentation

A heliostat and 0.125 meter f/24 telescope mounted on the roof of the JCMT entrance porch on Mauna Kea projected a 28-mm image of the Sun onto a slit of width 0.52 mm and length 4 mm (35×270 arcsec^2), behind which was placed a 4-segment continuously-variable filter wheel, rotated at 200 steps per revolution by stepping motor, at 1 revolution per second. Focussing optics re-imaged the slit onto a 1-mm InSb detector, while a multi-blade chopper placed in this beam modulated the resulting light at about 800 Hz. Three of the filter segments were within the pass-band of this detector, a single 2.5-4.5 μm filter (the "near IR" channel) with a single-step resolution of 0.045 μm resolution, and two 4.4-8.0 μm filters for which the detector sensitivity limited the observed spectrum to 5.4 μm. These latter two filters, on opposite sides of the filter wheel, covered the spectral region containing the CO fundamental V-R bands at 4.3-5.5 μm twice per second to a single-step resolution of about 0.08 μm. The resulting signals from the phase-sensitive detection system were digitized and stored in synchronism with the stepping motor drive and were tape-recorded along with standard time signals and displayed upon a high-speed chart recorder for monitoring and record-keeping during the eclipse. A beam-splitter fed a visual image through a 5×10 arcmin^2 slit onto an unfiltered Si photocell for visible eclipse monitoring. This signal was also digitized and recorded in synchronism with the millimeter wave signal monitored by the JCMT. A video camera recorded both the visual image and WWV time signals to provide an audio and video log-book of the experiment. A typical spectrum, recorded about 5 minutes before 2nd contact, is shown in terms of channel number in Figure 1, the CO band regions occupying channels 37-48 and 137-148 respectively.

3. Observing Conditions

The eclipse on Mauna Kea began when the Sun was only 8° above the horizon, or just a few degrees above the mountain summit, to the east of the JCMT. Thus, the early calibration spectra were taken at disk center through several air-masses. Totality occurred when the Sun had reached an elevation of 21° while 4th contact was observed at 37° elevation, at an air-mass of 1.66. Localized clouds were seen over the summit in the direction of the Sun soon after 1st contact but cleared through the central eclipse and totality periods, only to return again several times during the recovery beyond 3rd contact. These clouds did not affect the signal around totality. Indeed, the noise level on the signal decreased significantly around totality. Thin high clouds extended across the sky throughout the eclipse but did not appear to affect the IR signal.

The Moon moved across the Sun's disk at 0.519 arcsec per second. Thus, the spectrophotometer provided an angular resolution at the Sun's limb of about 0.25 arcsec in the CO band region and about twice this figure for the near IR band. Several calibration runs on the solar disk center were recorded before and after the eclipse. Digital recording of the period around totality was started 5 minutes before 2nd contact when the width of the remaining arc of the solar disk had become less than about 1/2 of the slit length. The whole photometer head was rotated to align the slit to be perpendicular to the eclipsed limb. This slit alignment for 2nd contact was within a few degrees of optimum alignment for 3rd contact and no attempt was made to re-align the slit during totality.

4. Results

Eclipse curves are shown in Figures 2a and b for the few seconds around 2nd and 3rd contacts respectivley, for a single channel in the 4.0 μm "continuum" region where solar CO absorption lines are absent and where atmospheric absorption is low, for a single channel at 4.6 μm within the region of strong solar CO absorption and for the visible channel at 2nd contact. These data have been normalized to agree at a point some 10 seconds before 2nd contact for Figure 2a and 10 seconds after 3rd contact for Figure 2b, and an equivalent solar-disk distance scale has been placed upon these graphs. It is immediately apparent that the CO-band 2nd contact occurs a small but significant time later than that for the visible or continuum near-IR contact, and that the order is reversed for the 3rd contact data by about the same time difference. This is interpreted to indicate that the CO bands are exhibiting a flash spectrum in showing remanent emission up to about 120 km above the near IR and the visible limbs, or about 460 km above the $\tau_{0.5} = 1$ level in the solar atmosphere.

Figure 3 shows a more detailed 2nd-contact differential eclipse curve using normalized and averaged data from 5 adjacent channels in the near IR continuum,

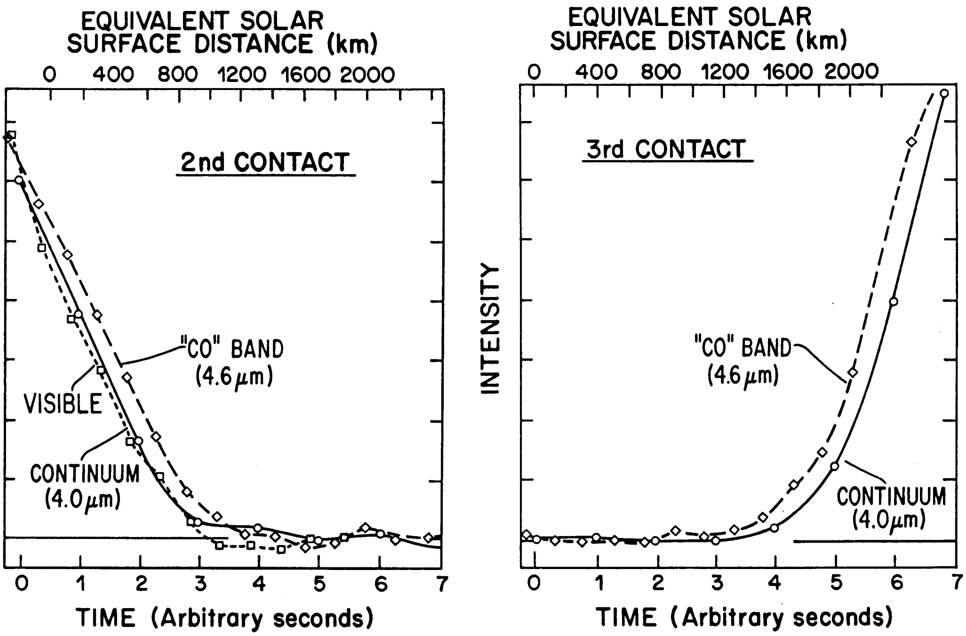

Fig. 2. Panels a and b show respectively the occultation curves for the 2nd and 3rd contacts, for single channels in the visible, near-IR continuum, and CO band regions. One second of time corresponds to 0.519 arcsec.

from 4 adjacent channels in the CO-band region and from a smoothed visible channel record. A first attempt has been made in these data to calibrate the intensity in terms of the fraction of equivalent disk-center intensity per resolution element (0.519 arcsec wide, at 1 spectrum per second) using early and late spectra for this radiometric calibration. This absolute intensity scale is tentative only and is dependent upon the atmospheric-extinction correction over the wide range of airmass encountered during this eclipse. The visible record has been normalized to the expected limb darkening at $\mu = \cos\theta = 0.2$ from standard limb darkening curves and agrees reasonably with the eclipse curve of Weart (unpublished, but shown in Athay (1976)) which is shown for comparison with the visible curve. The equivalent visible eclipse record of Makita (1972), modeled by Noyes and Kalkofen, shows a much steeper final decrease than either the present record or that of Weart. The scale height of the final visible limb decrease for the present data is about 840 km compared to 535 km for the data of Weart and about 100 km for Makita's curve. By comparison, the IR continuum scale height is 175 km while that for the CO band region is 185 km. In this graph, the solar limb position has been placed at the point of inflection of the near IR continuum curve to match these other visible

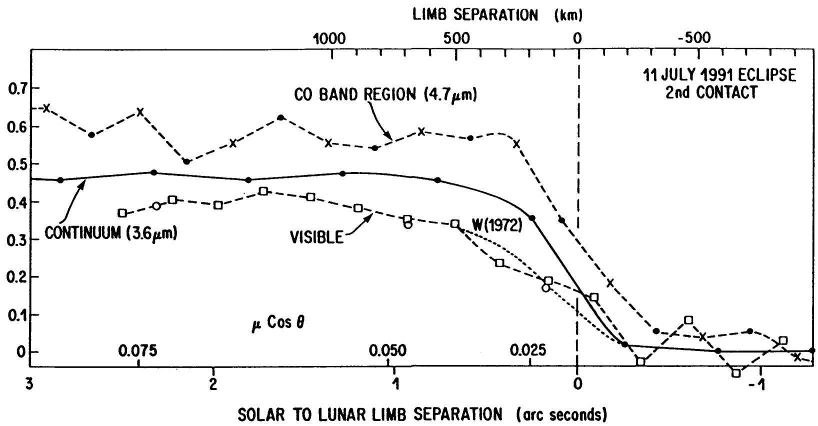

Fig. 3. Differential eclipse curve for 2nd contact, plotted as the fraction of the equivalent disk-center intensity, for averages of 5 channels in the continuum band, 4 channels in the CO band region, and the visible channel. The limb position has been placed at approximately the point of inflection of the final limb decrease. W(1972) refers to the visible eclipse curve of Weart.

eclipse curves. The zero-point values for height and $\mu = \cos\theta$ scales have been fixed at this level. Establishment of the true limb position requires further analysis of the visible eclipse curve, but is unlikely to be inaccurate in an absolute sense by more than 150 km.

The dashed curve in Figure 3 shows the relative extension of the CO-band region beyond the near IR and visible limb by 125 ± 15 km, with maybe a more extensive but low intensity (0.05 of the central intensity) residual out to 640 km above the near-IR limb. There is evidence of limb darkening within the last few arcseconds in all of these eclipse curves. Analysis is still proceeding on the 3rd contact data but these results may be affected by a large prominence noted near this contact point on eclipse photographs.

5. Conclusions

The present near-IR eclipse measurement at wavelengths containing the CO fundamental V-R band shows clear evidence for an extension (of about 125 km) of the solar limb beyond the visible and near-IR continuum limbs. If this is interpreted as the flash spectrum of the composite CO band, then this indicates that the main CO emission arises in a layer slightly below the temperature minimum, at a depth of about 465 km above the photosphere. This result can be compared to the $\tau_{CO} = 1.0$ level predicted by two model atmospheres used in the recent non-LTE investigation of Ayres and Wiedemann (1989). These are the semi-empirical "hot" chromosphere model of Avrett (1985) and radiative equilibrium model of Anderson (1989), which place this level 90 and 220 km above the visible limb, or 430 km and 560 km above the $\tau_{0.5} = 1.0$ level in the photosphere, respectively.

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