NASA SP-3086

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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INTRODUCTION

Excellent near-infrared spectra of the outer planets have been obtained in recent years with a Michelson interferometer and lead sulfide detectors. Connes, Connes, and Maillard (ref. 1) have published a Jupiter spectrum with a resolution of approximately 0.4 cm^{-1} in the range from 5700 to 8500 cm^{-1} and a Saturn spectrum with a resolution of approximately 1.7 cm^{-1} in the range from 5900 to 8500 cm^{-1}. Maillard, Combes, Encrenaz, and Lecacheux (ref. 2) recently reported an improved Jupiter spectrum with a resolution of approximately 0.22 cm^{-1} in the spectral range from 4000 to 12 000 cm^{-1}. No infrared spectra of Uranus have apparently been published.

The purpose of this report is to present new Jupiter, Saturn, and Uranus infrared spectra. The Uranus spectrum was obtained at a resolution of approximately 32 cm^{-1} in the range from 6000 to 10 000 cm^{-1}. Saturn, Jupiter, and Sun spectra were measured with a resolution of approximately 0.5 cm^{-1} in the range from 6000 to 10 750 cm^{-1}. Relative comparisons of Saturn, Jupiter, and Sun spectra are easily made because all spectra were obtained with the same instrument and at the same resolution.

EXPERIMENTAL PROCEDURES

During November 1972, observations of Saturn and Jupiter were made with the Coudé focus of the 272-cm (107-in.) telescope at the McDonald Observatory. To minimize the effect of planetary rotation on spectral resolution, an aperture was used for Jupiter measurements that permitted only the central third of the disk to enter the interferometer (ref. 2). An aperture was used for observing Saturn that excluded the rings but included as much of the planetary surface as possible. The Sun measurements were made during the day before the planetary measurements were made; a perforated screen was placed over the telescope mirror to reduce the light intensity. To observe the different spectra, measurement times of 50 min for Jupiter and 150 min for Saturn were required. Only a few minutes were required for observing the Sun spectra.

Uranus was measured in March 1972. The results of three 1-hr runs were added to determine the final spectrum. The measurements were made at a resolution of 16 cm^{-1}. Because the resulting data contained too much noise, the resolution was reduced mathematically to 32 cm^{-1}. The resulting spectrum had a peak signal-to-noise ratio of approximately 20.

The Michelson interferometer used for the measurements was a rapid-scan instrument in which successive scans were coadded to yield a final interferogram. For the 0.5-cm^{-1} spectra, the displacement of the moving interferometer mirror was 1 cm, and each stroke required 16 sec. The interferograms were digitized at 2^{17} intervals and coadded on a magnetic disk. The digitization intervals were generated by quadrupling the interference waves from a helium neon laser. These intervals represent an oversampling of the interferogram, performed to maximize signal-to-noise ratios. The detector was a liquid-nitrogen-cooled germanium photovoltaic cell, which was sensitive in the range from 6000 to 10 750 cm^{-1}.

The interferogram is sampled at intervals determined by the interference waves generated from a reference helium neon laser beam. When the reference laser beam and the telescope axis are perfectly alined, the spectral line positions are accurately determined from the laser wavelength.

However, because this alinement was difficult, there were slight shifts in the line positions. The telescope beam convergence ($f/32$) and the variation of the refractive index of air with wavelength also produced wavelength shifts. All these factors were taken into account by adjusting the wavelength scale so that the terrestrial water vapor absorption lines were correctly located. On the average, vacuum wavelengths in the resulting spectra are accurate to within ± 0.1 cm^{-1}.

Apodization was not applied to the interferograms; thus, the measured spectral resolution was approximately equal to the full instrumental resolution of 0.5 cm^{-1} (estimated from the half width of terrestrial water vapor lines). A five-point interpolation was performed on the transformed interferogram to provide smooth plots and precise line locations.

RESULTS

A plot of the Uranus spectrum, together with Saturn, Jupiter, and Sun spectra for comparison, is shown in figure 1. All spectra are shown at a resolution of 32 cm^{-1}. No corrections have been applied for the instrument function, atmospheric transmission, or detector response. The plots are scaled such that the maximum value in the 6000- to 10 000-cm^{-1} range is assigned a value of unity. No data are shown in the 7100- to 7400-cm^{-1} range because of water vapor absorption in that spectral range. The plots clearly indicate the substantially larger methane and hydrogen absorptions of Uranus as compared to those of the other outer planets.

The necessity for a long exposure time in making Uranus measurements may introduce contamination caused by terrestrial airglow. A comparison of the Uranus spectrum, as shown in figure 1, with an airglow spectrum measured with the Michelson interferometer used in experiments previously mentioned indicates that the spectral range near 6350 cm^{-1} is probably caused by the 4-2 band of the terrestrial hydroxyl airglow and that the features near 6650 cm^{-1} are probably

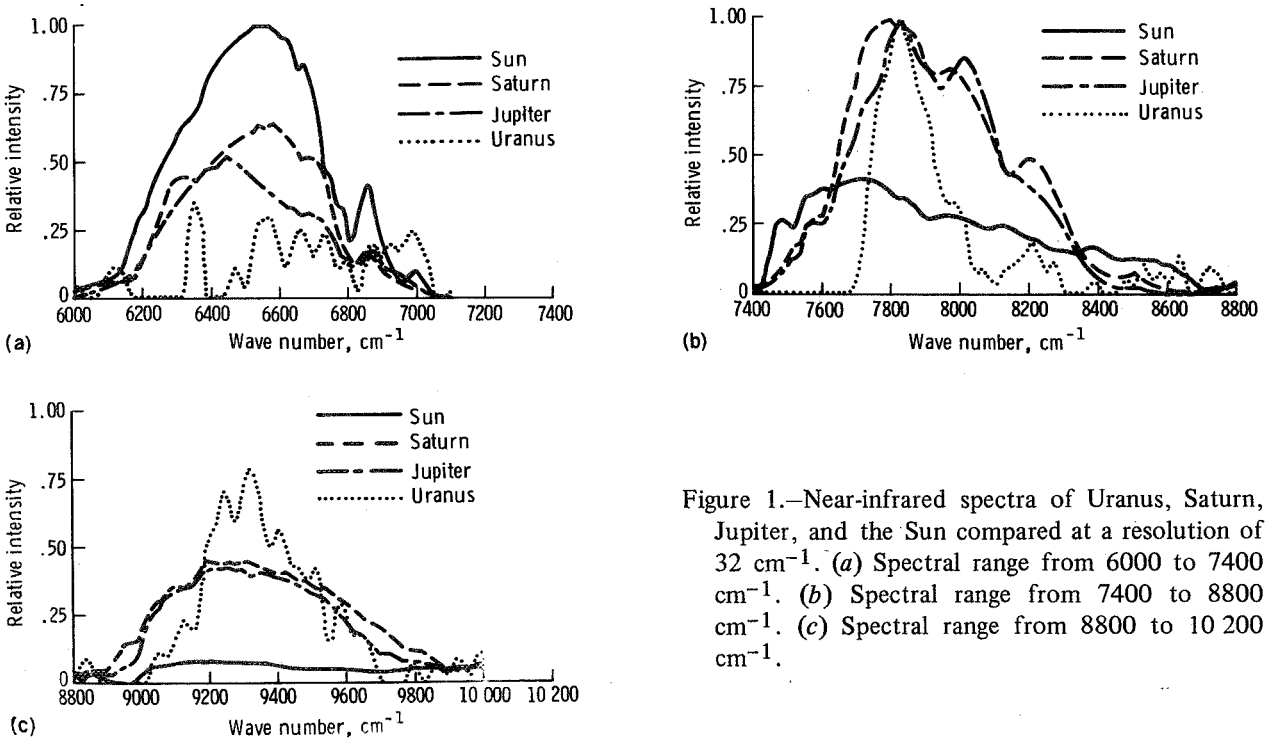

Figure 1.—Near-infrared spectra of Uranus, Saturn, Jupiter, and the Sun compared at a resolution of 32 cm^{-1}. (*a*) Spectral range from 6000 to 7400 cm^{-1}. (*b*) Spectral range from 7400 to 8800 cm^{-1}. (*c*) Spectral range from 8800 to 10 200 cm^{-1}.

caused by the 3-1 hydroxyl band. Other spectral regions are believed to be significantly unaffected by airglow.

A comparison of the ratio spectrum of Uranus and the Sun with similar ratio spectra for Jupiter and Saturn is shown in figure 2. The ratio spectrum is a representation of the relative reflectivity spectrum of the planet with solar energy distribution, instrument function, detector response, and atmospheric transmission removed. These plots show more clearly the increased methane and hydrogen absorptions of Uranus compared with those of the other outer planets. No data are given between 6900 and 7500 and between 8500 and 9000 because the values were negligibly low.

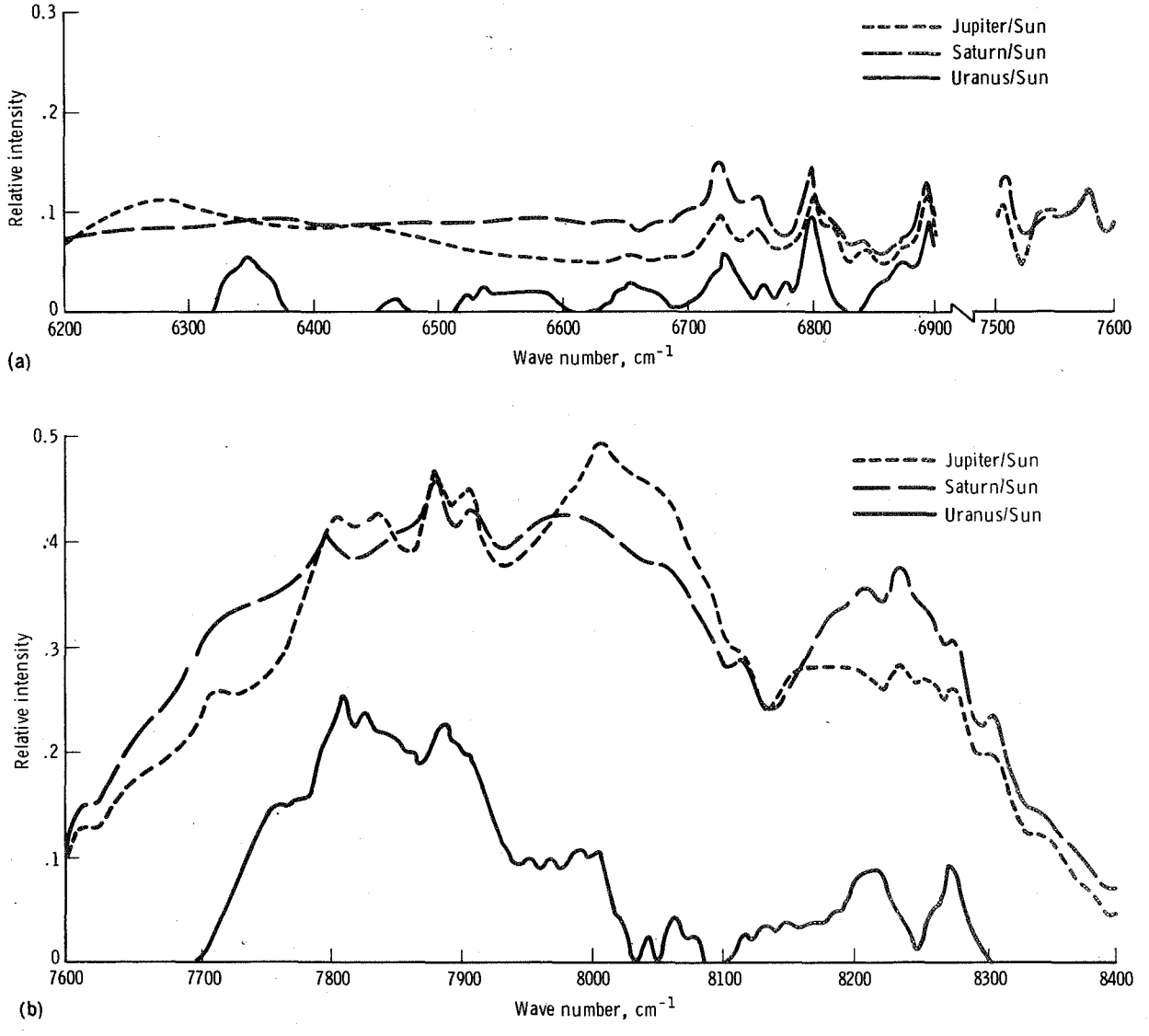

Figure 2.–Near-infrared ratio spectrum of Uranus and the Sun compared with Jupiter and the Sun and Saturn and the Sun ratio spectra at a resolution of 32 cm^{-1}. (*a*) Spectral range from 6200 to 7600 cm^{-1}. (*b*) Spectral range from 7600 to 8400 cm^{-1}.

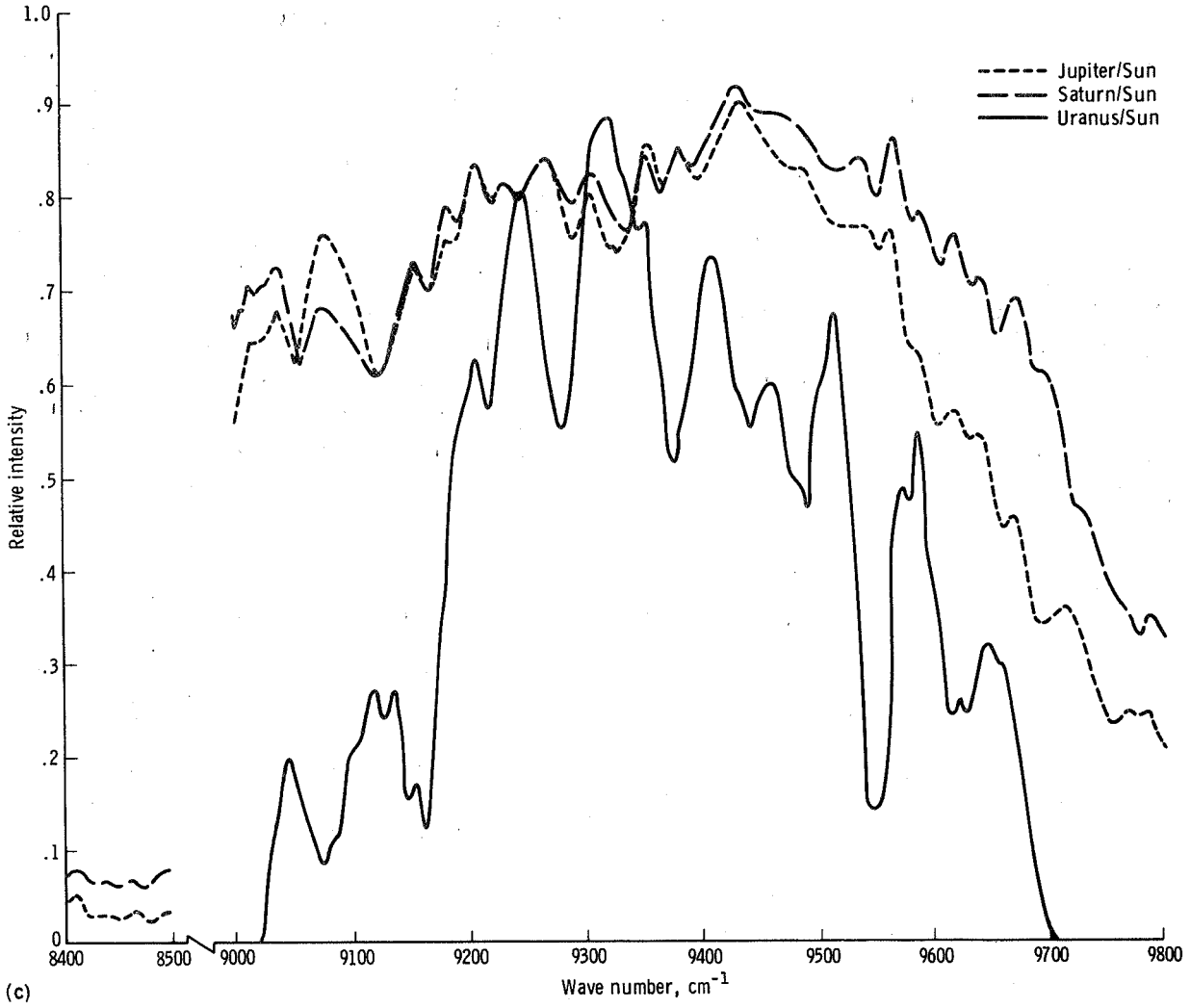

Figure 2 (concluded).—Near-infrared ratio spectrum of Uranus and the Sun compared with Jupiter and the Sun and Saturn and the Sun ratio spectra at a resolution of 32 cm^{-1}. (*c*) Spectral range from 8400 to 9800 cm^{-1}.

Jupiter, Saturn, and Sun spectra in the range from 6000 to 10 760 cm^{-1} are shown in figure 3. The abscissa is the spectral position in wave numbers (cm^{-1}) with 30 wave numbers plotted on each page. The ordinate of each plot is the approximate signal-to-noise value, defined as the ratio of the spectral intensity to the standard deviation of the signal outside the sensitive region of the detector. The plots on each page are individually scaled to achieve maximum use of the ordinate scale; the minimum and maximum values of the ordinate are given at the top of each page. In these plots, the signal-to-noise values range from approximately 5 to 100. No corrections have been applied for the instrument function, atmospheric transmission, or detector response. The positions of terrestrial water and carbon dioxide absorptions with cross sections larger than 10^{-23} cm^{-1} (ref. 3) are marked with a "T" at the bottom of the plots. (The terrestrial oxygen band near 7880 cm^{-1} is not marked.) No data are given between 6990 and 7400 cm^{-1} because of strong terrestrial water vapor absorption in this region. The Doppler shift was 0.90 cm^{-1} to lower wave numbers (elongation E

76°) for Jupiter and 0.85 cm^{-1} to higher wave numbers (elongation W 114°) for Saturn. A comparison of the Jupiter spectrum of figure 1 with that cited in reference 1 at about the same resolution shows the spectra to be virtually identical in regions of high signal-to-noise ratio (after allowance for the Doppler shift).

Figure 4 has been constructed to aid studies of the continuum reflection and molecular absorption bands. Parallel plots of the ratio of Saturn to the Sun, Jupiter to the Sun, and Jupiter to Saturn are shown. In preparing these plots, the planetary spectra have been shifted an amount corresponding to the Doppler shift. Terrestrial absorptions are then shifted relative to one another in the solar and planetary spectra. The ratios are distorted correspondingly at these points, which are marked with a "T" at the bottom of the plot. Noise fluctuations occasionally produced large ratio values, which led to difficulties with the choice of the ordinate scale. To minimize this problem, each plot (45 cm^{-1} long) was individually scaled, and ratio values that exceeded three times the mean value were set equal to zero. Normally, the zero values that result from this calculation can be easily distinguished from true absorptions.

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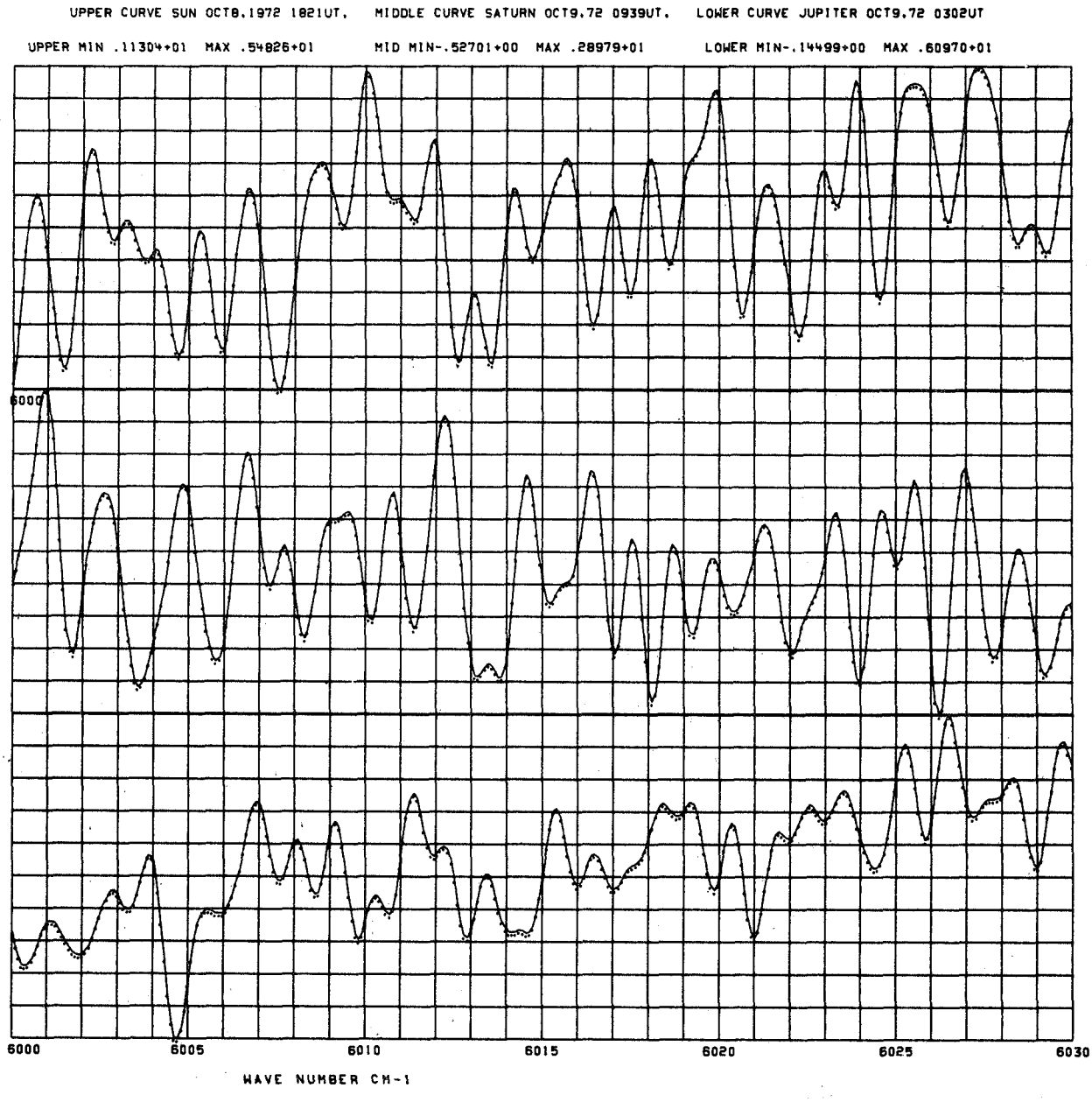
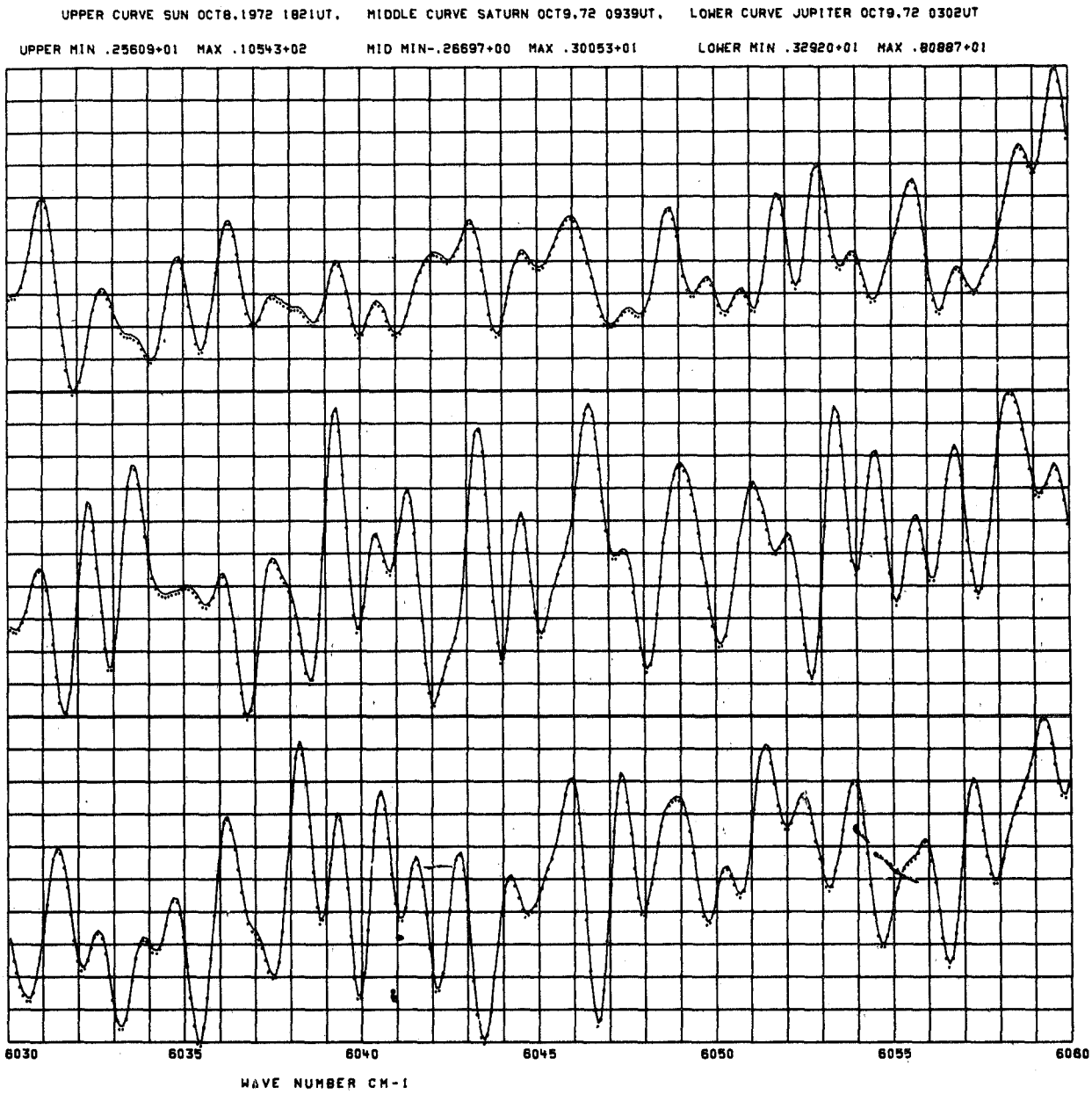


Figure 3.–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.



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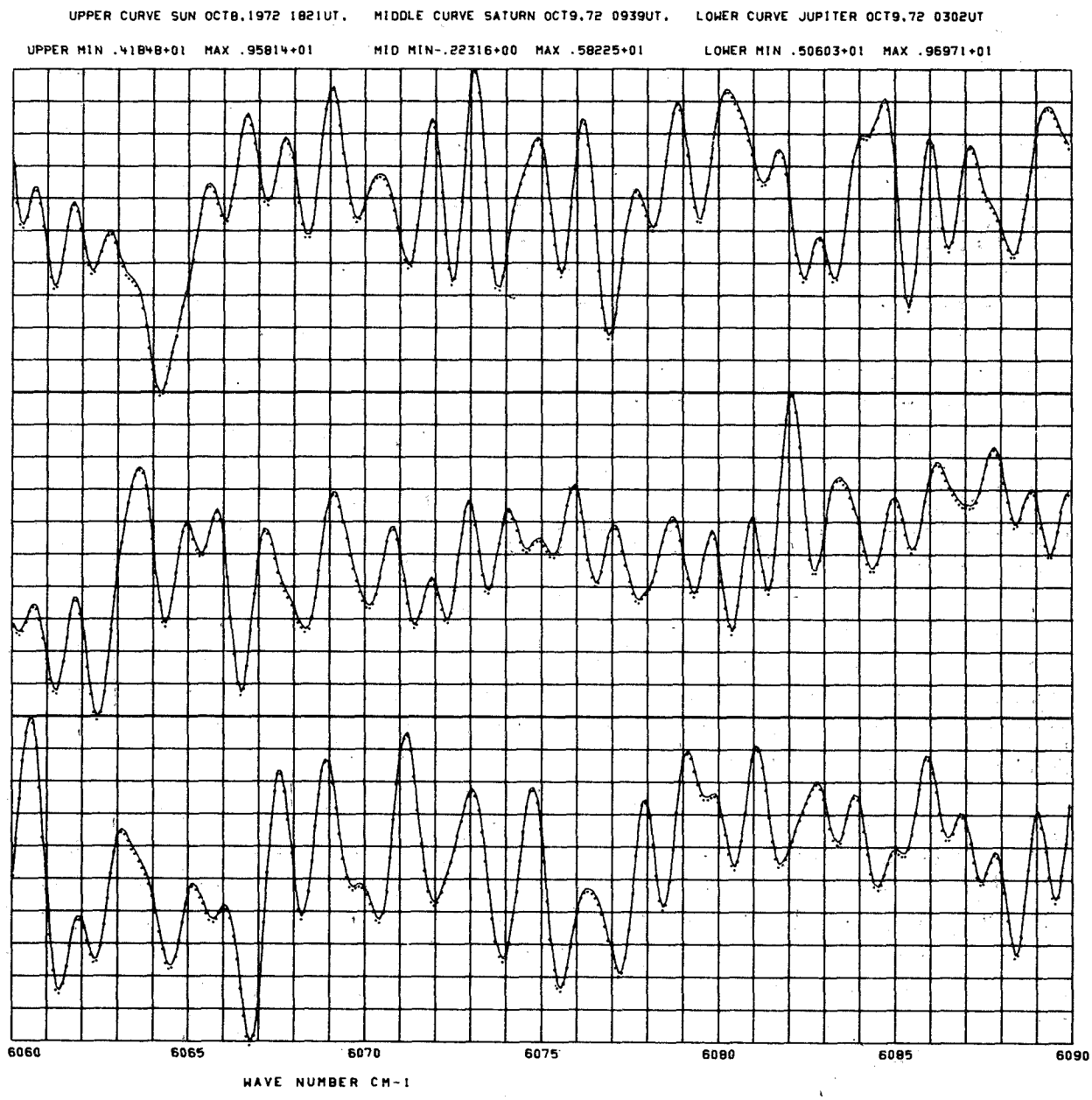

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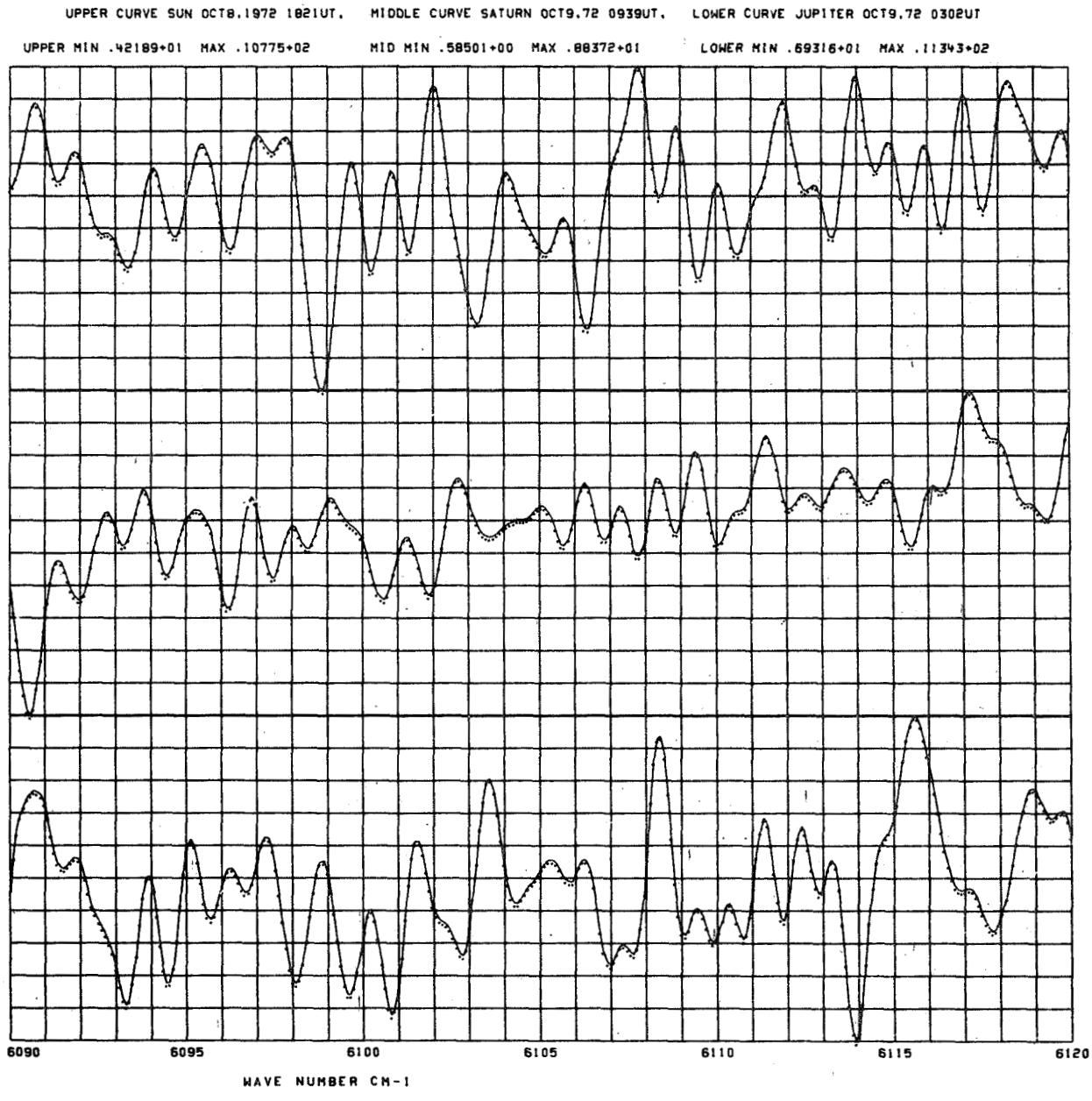

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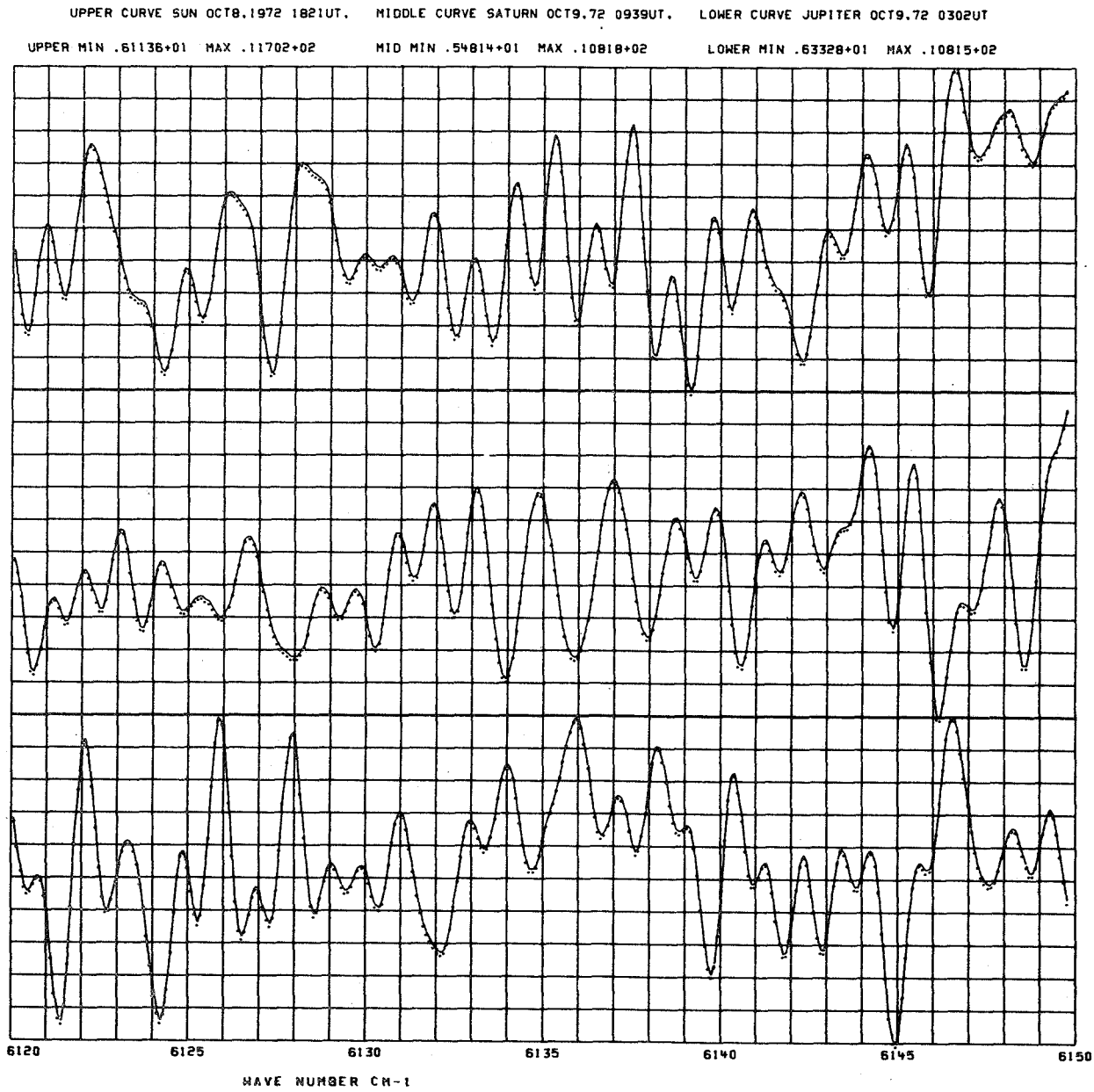

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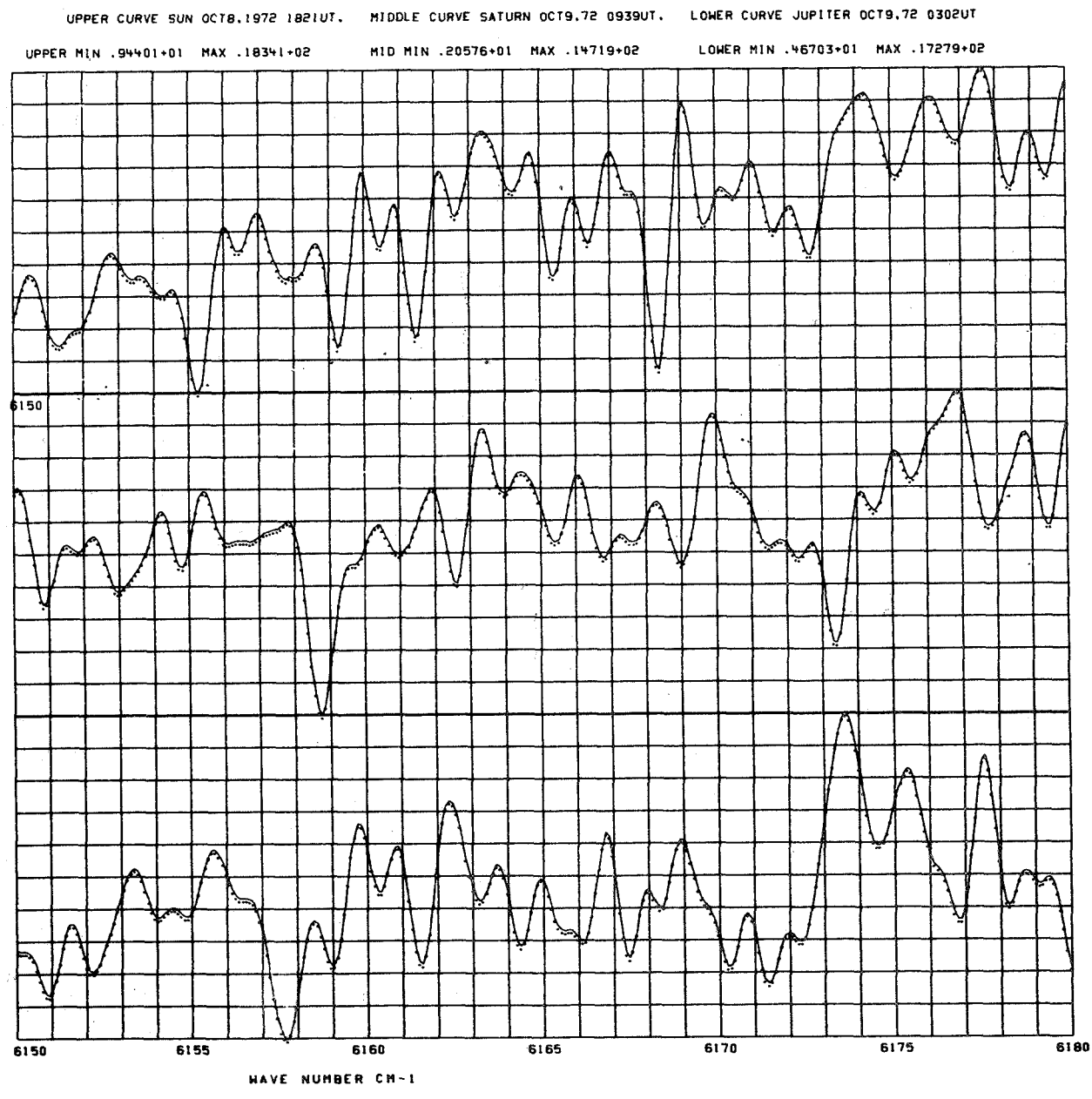

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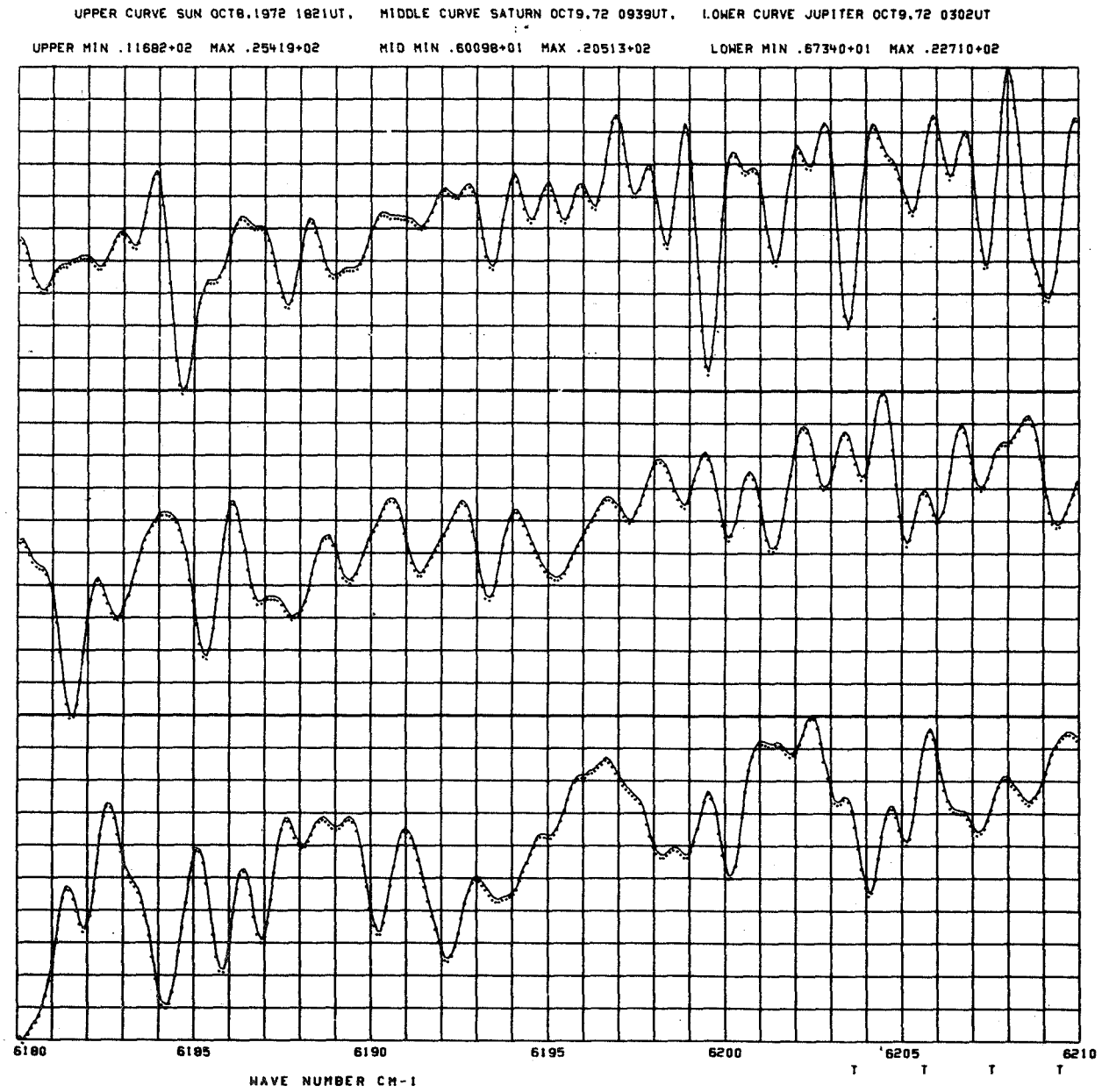

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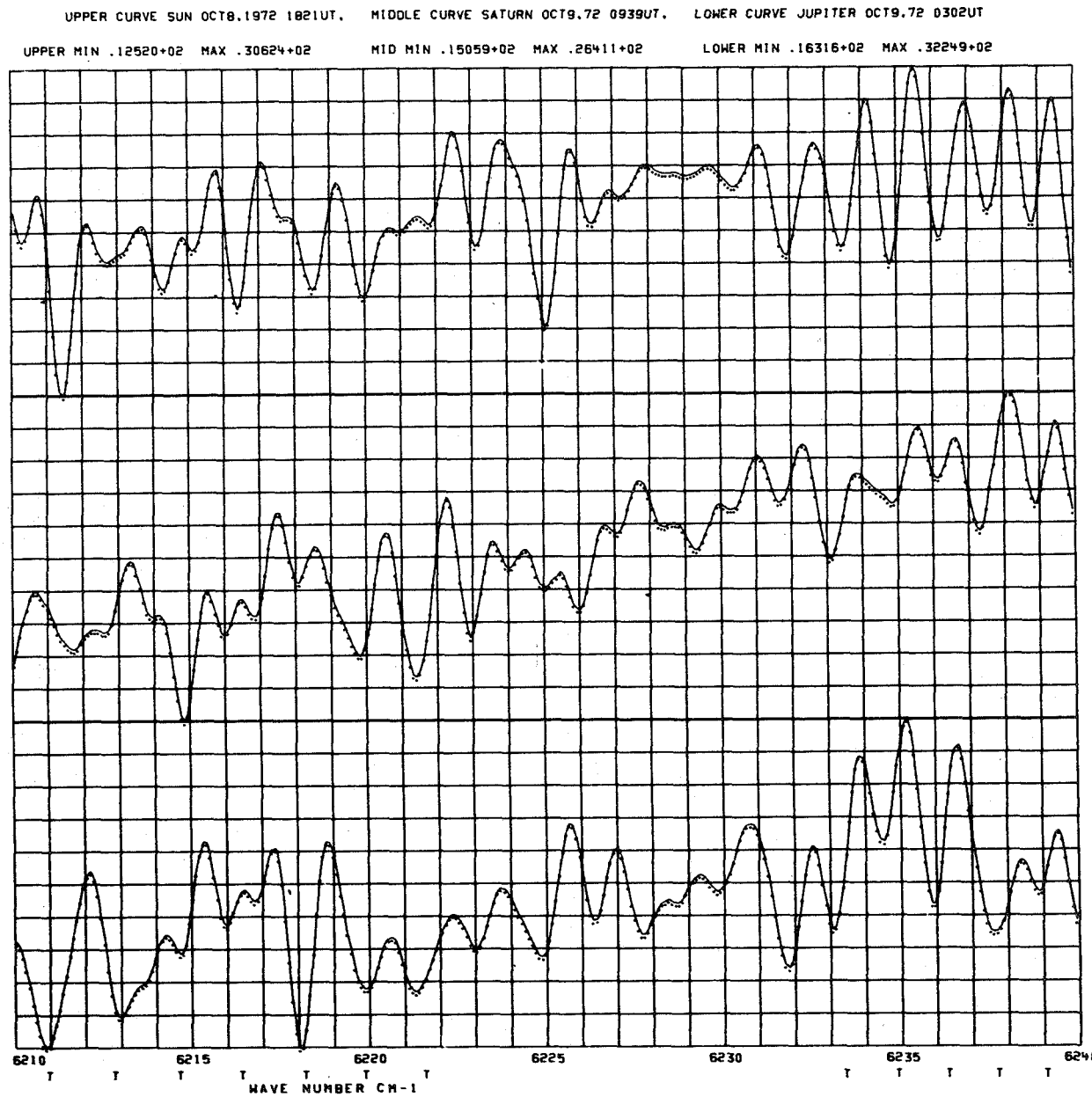

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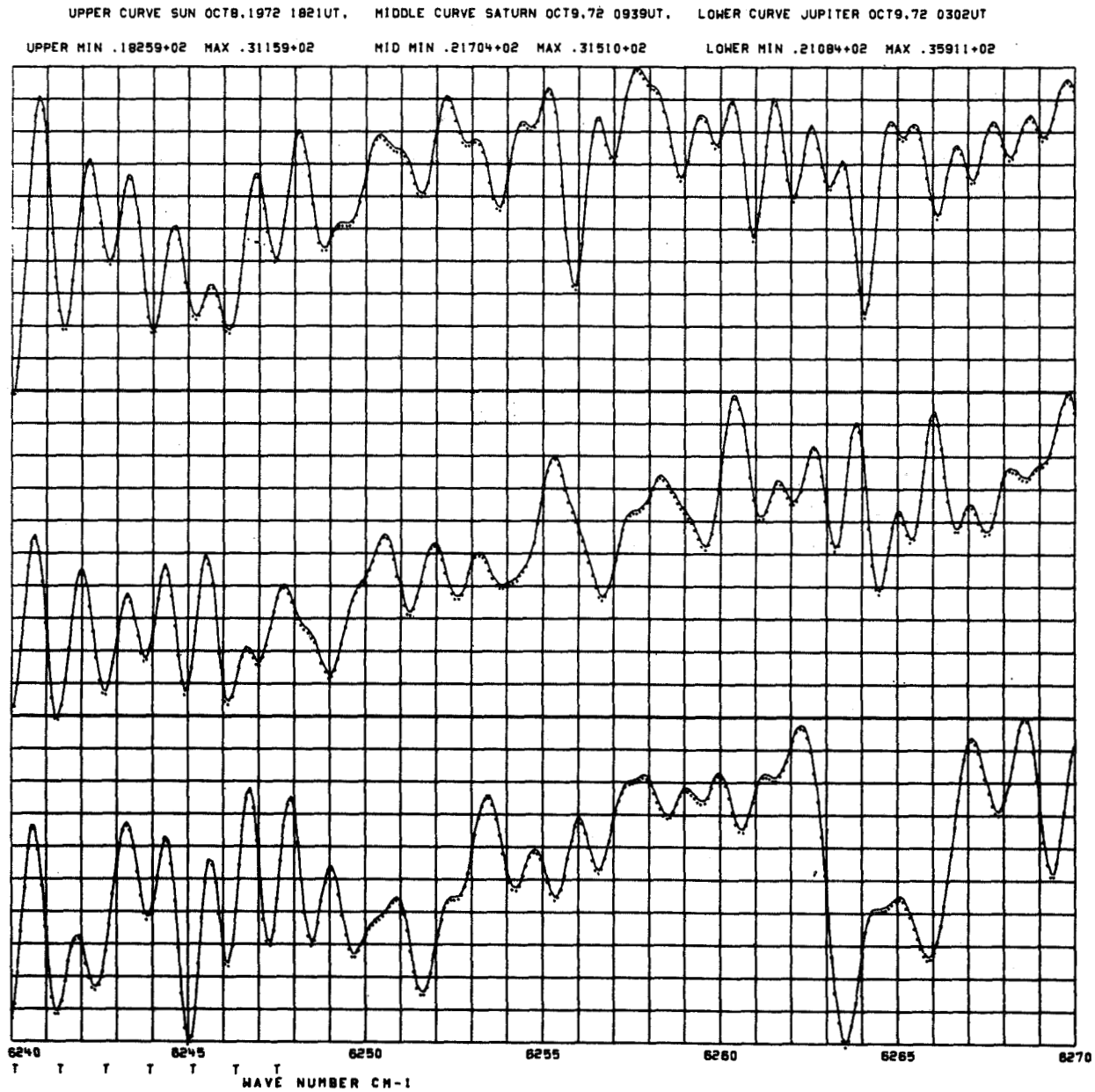

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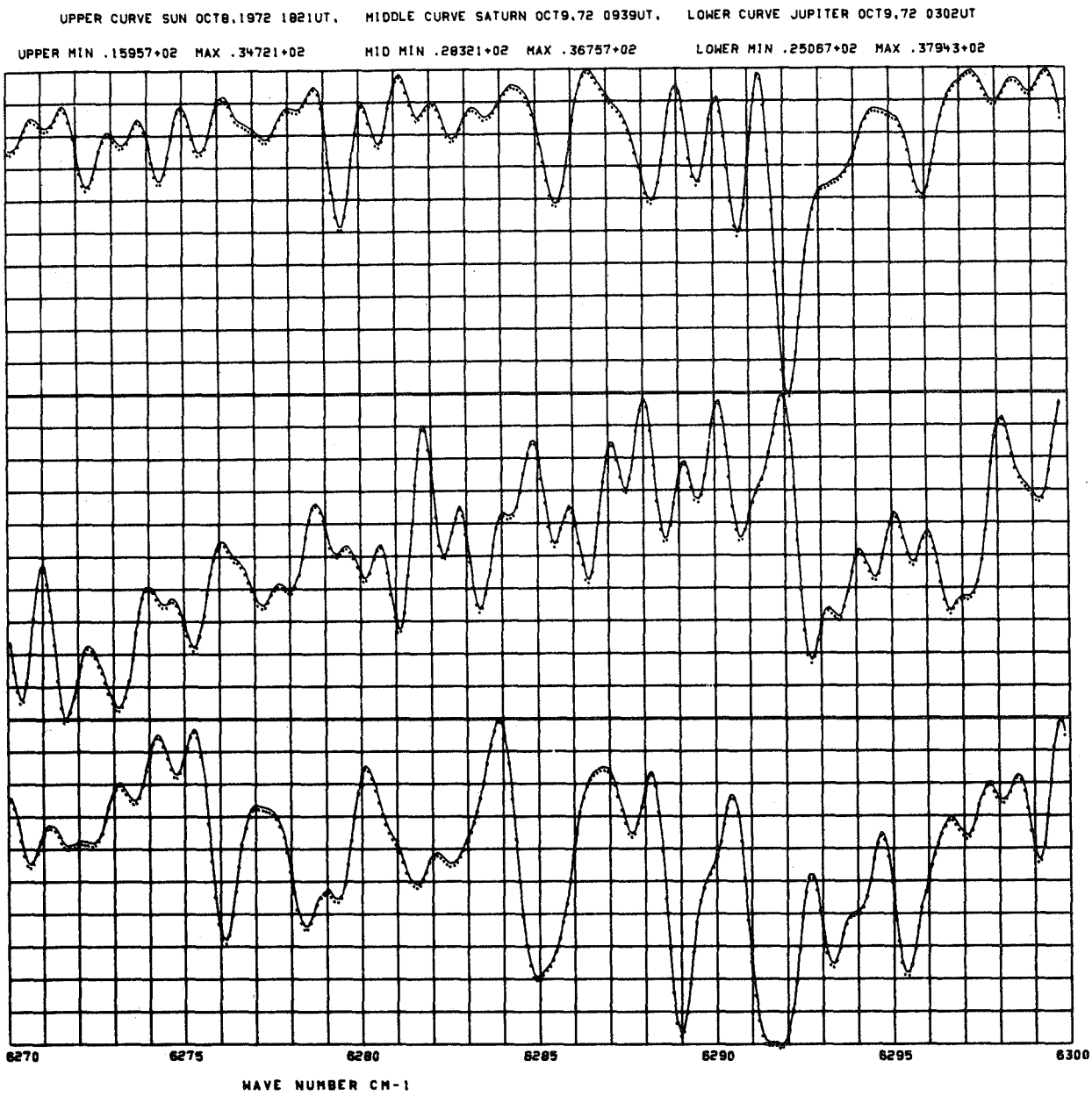

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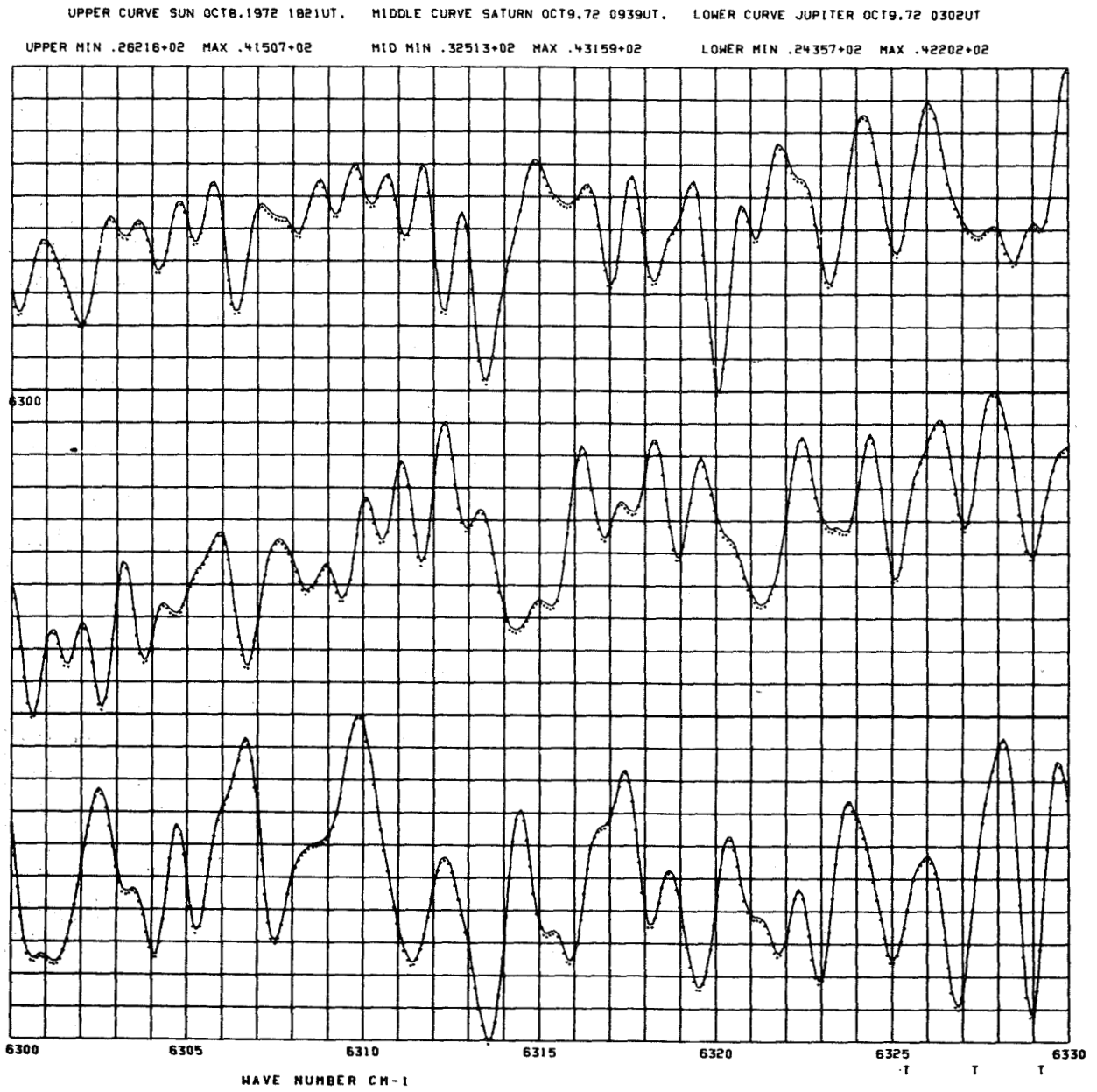

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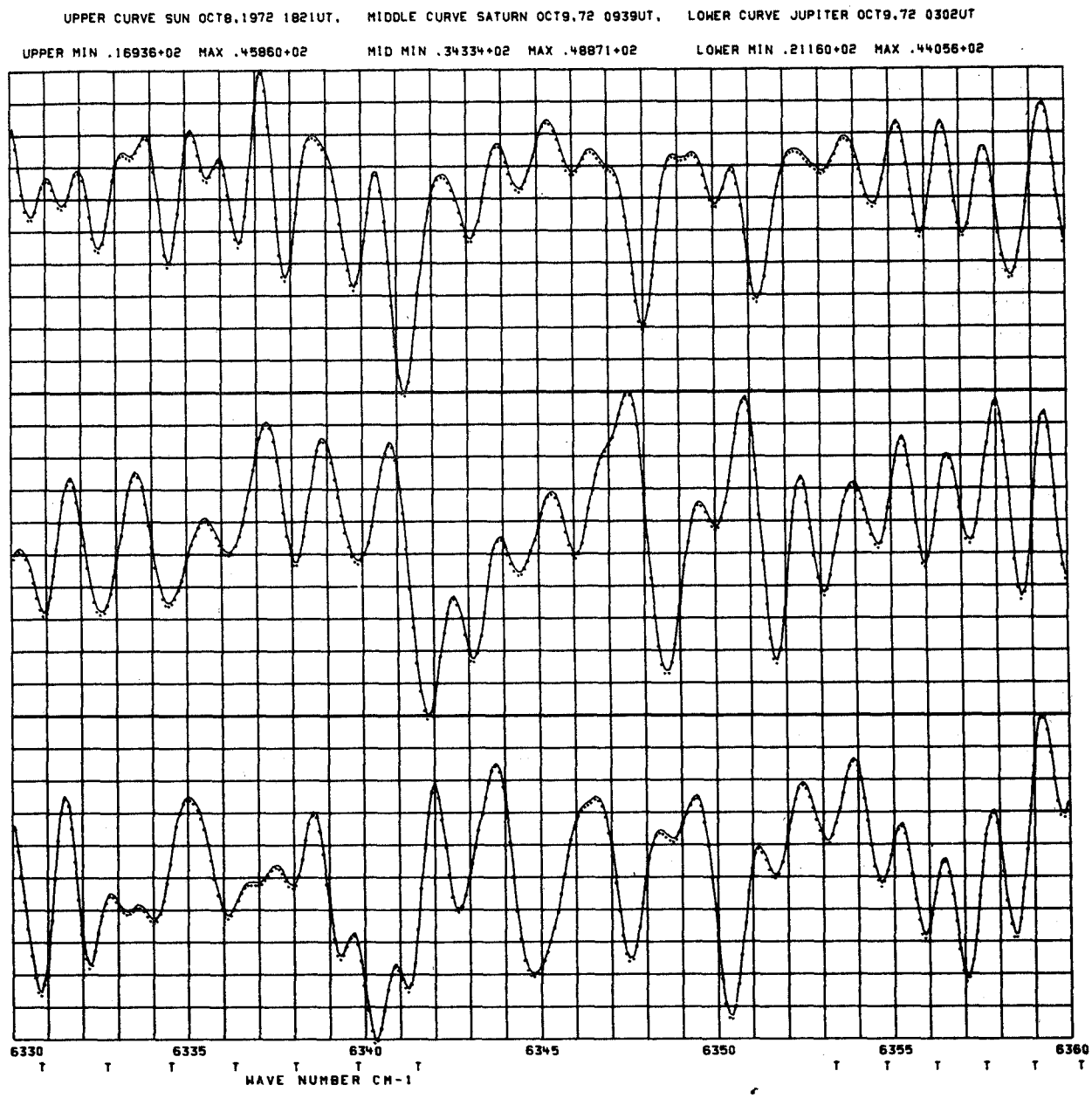

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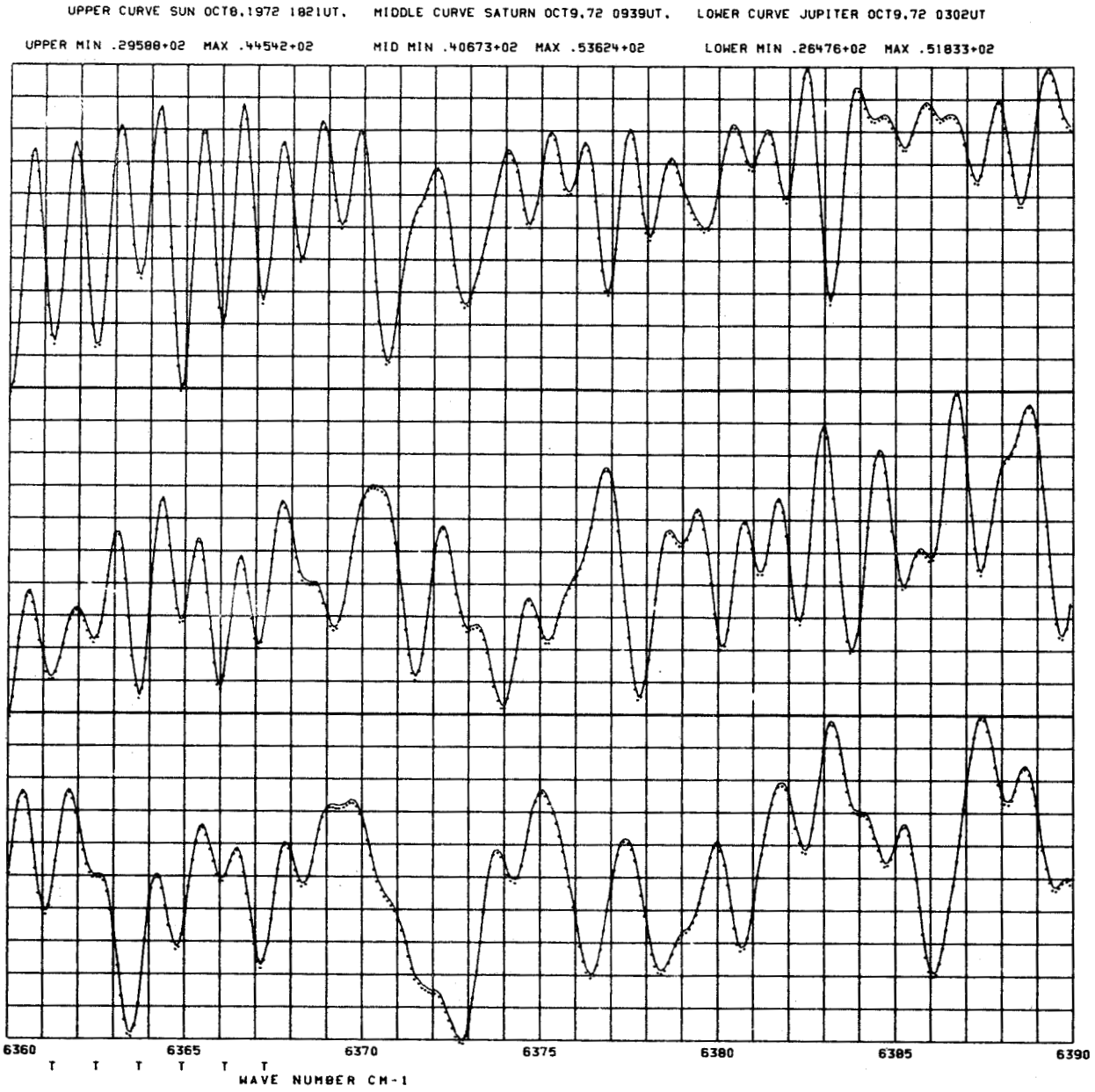

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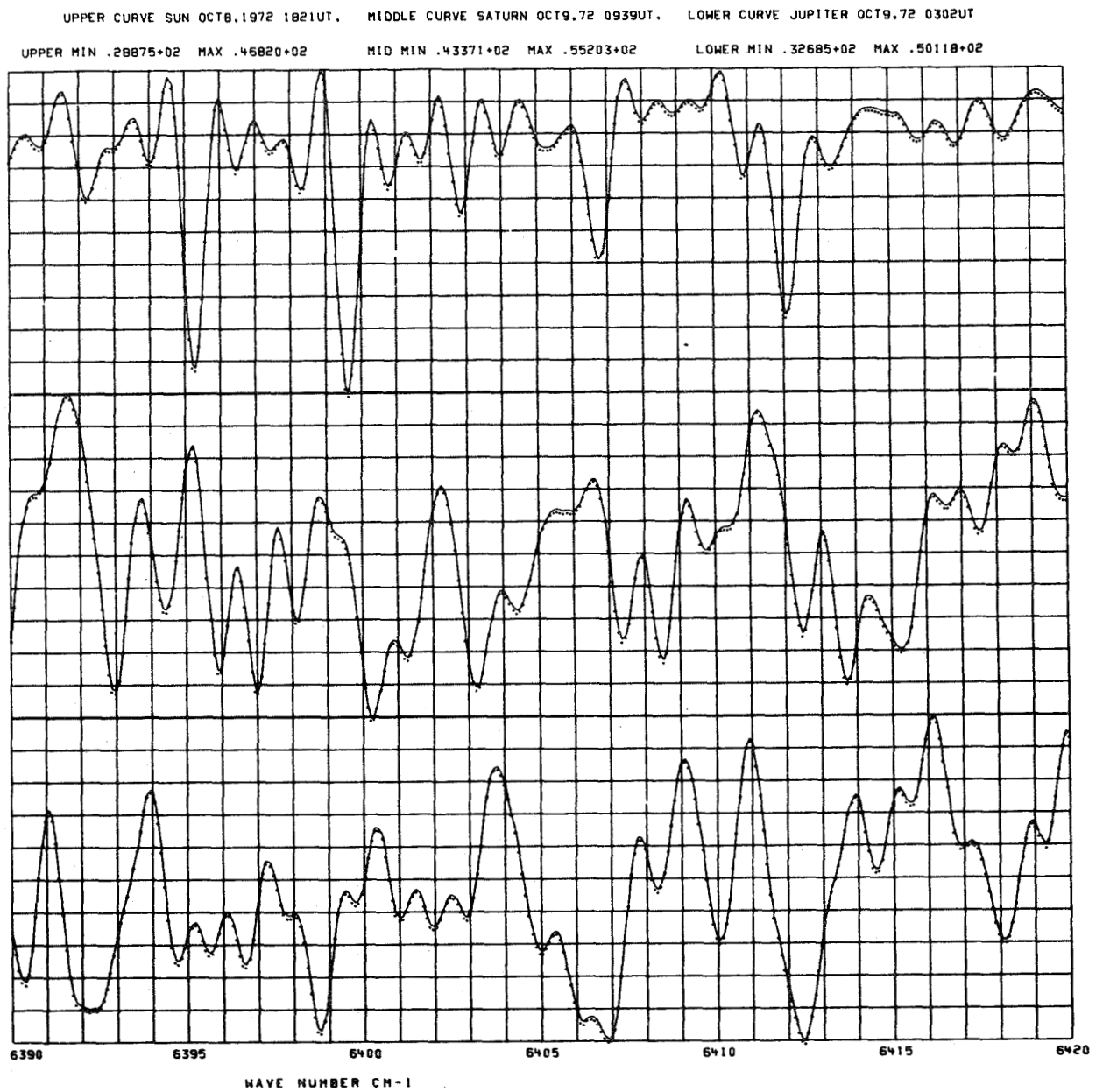

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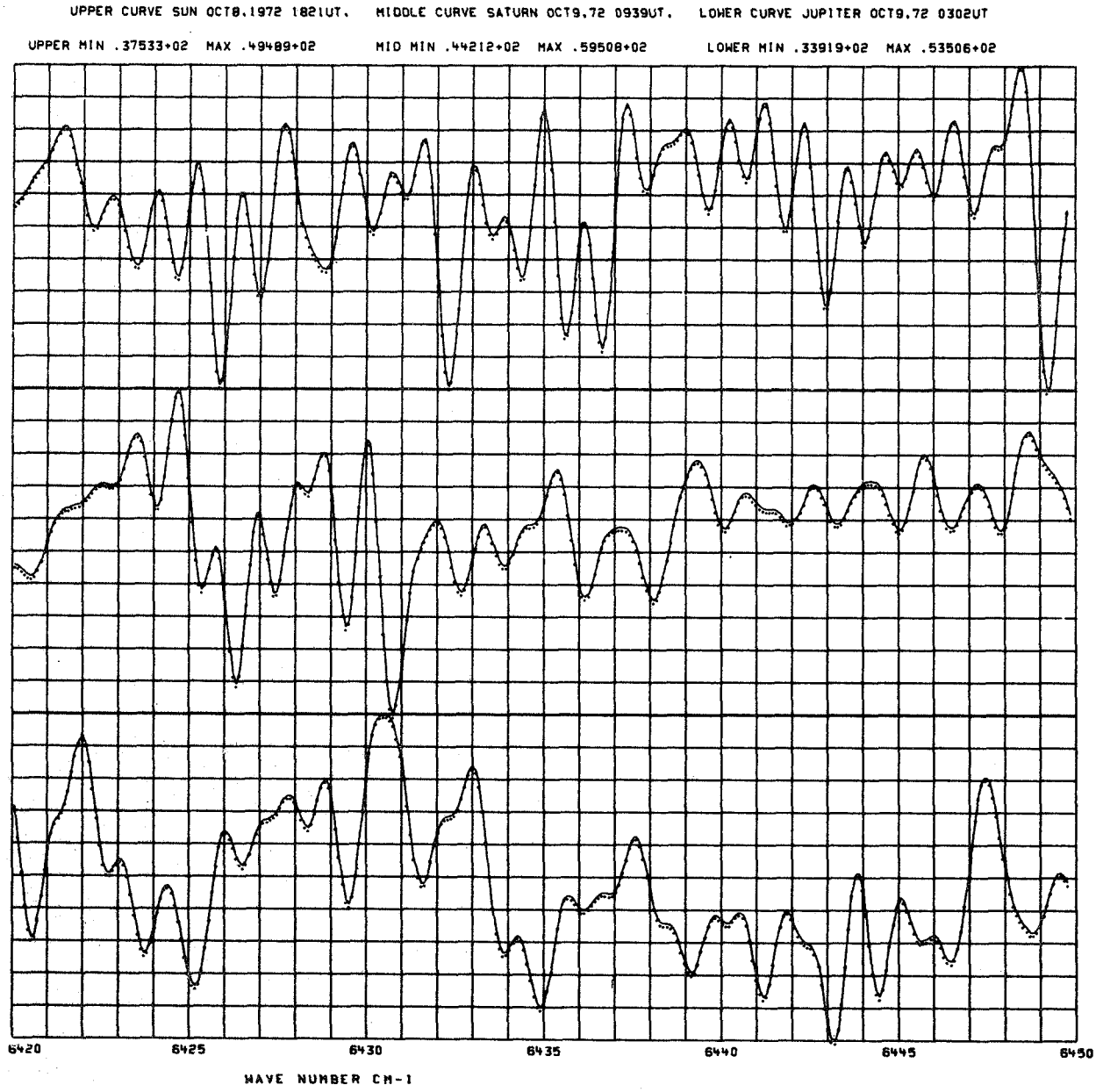

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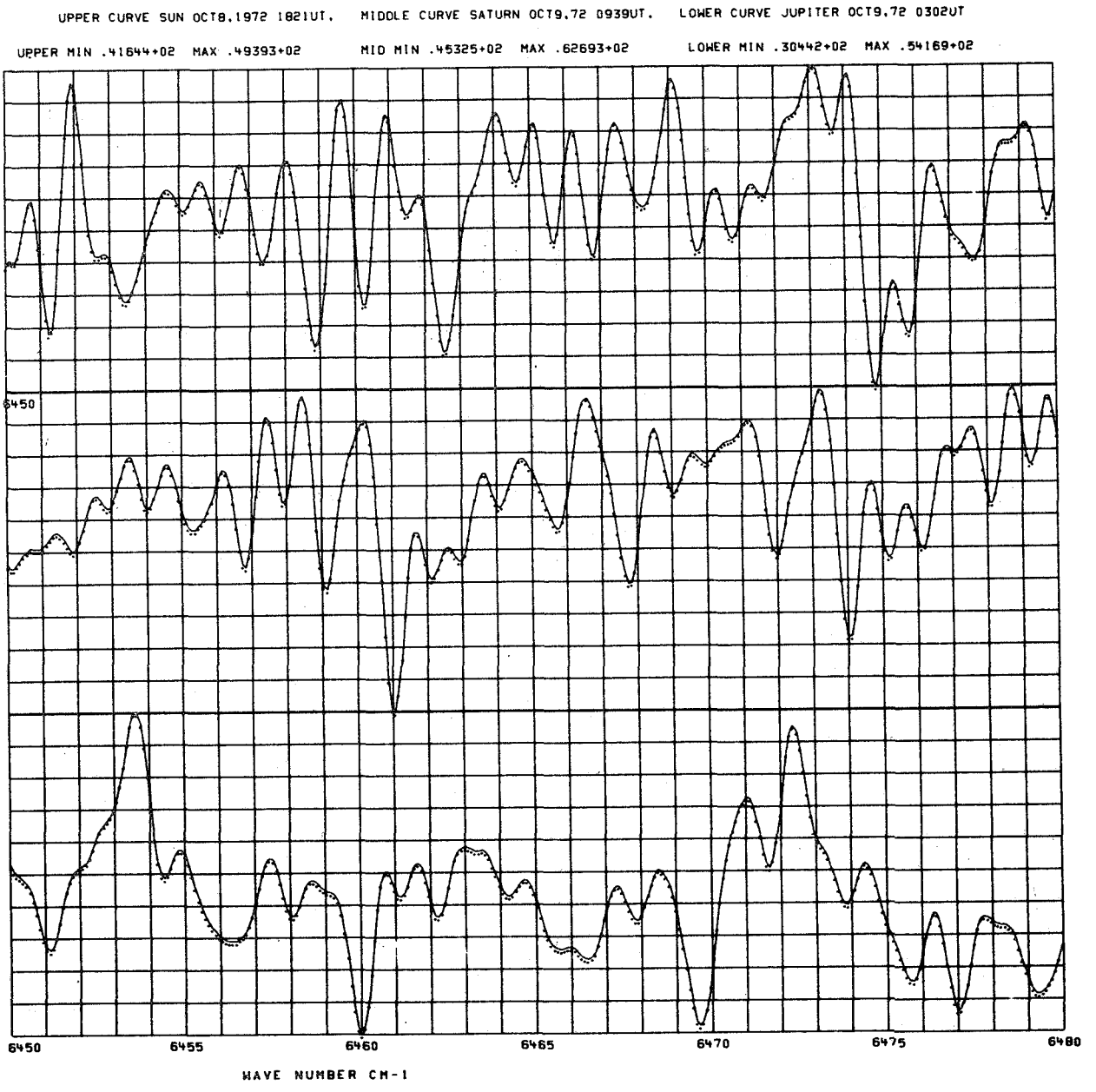

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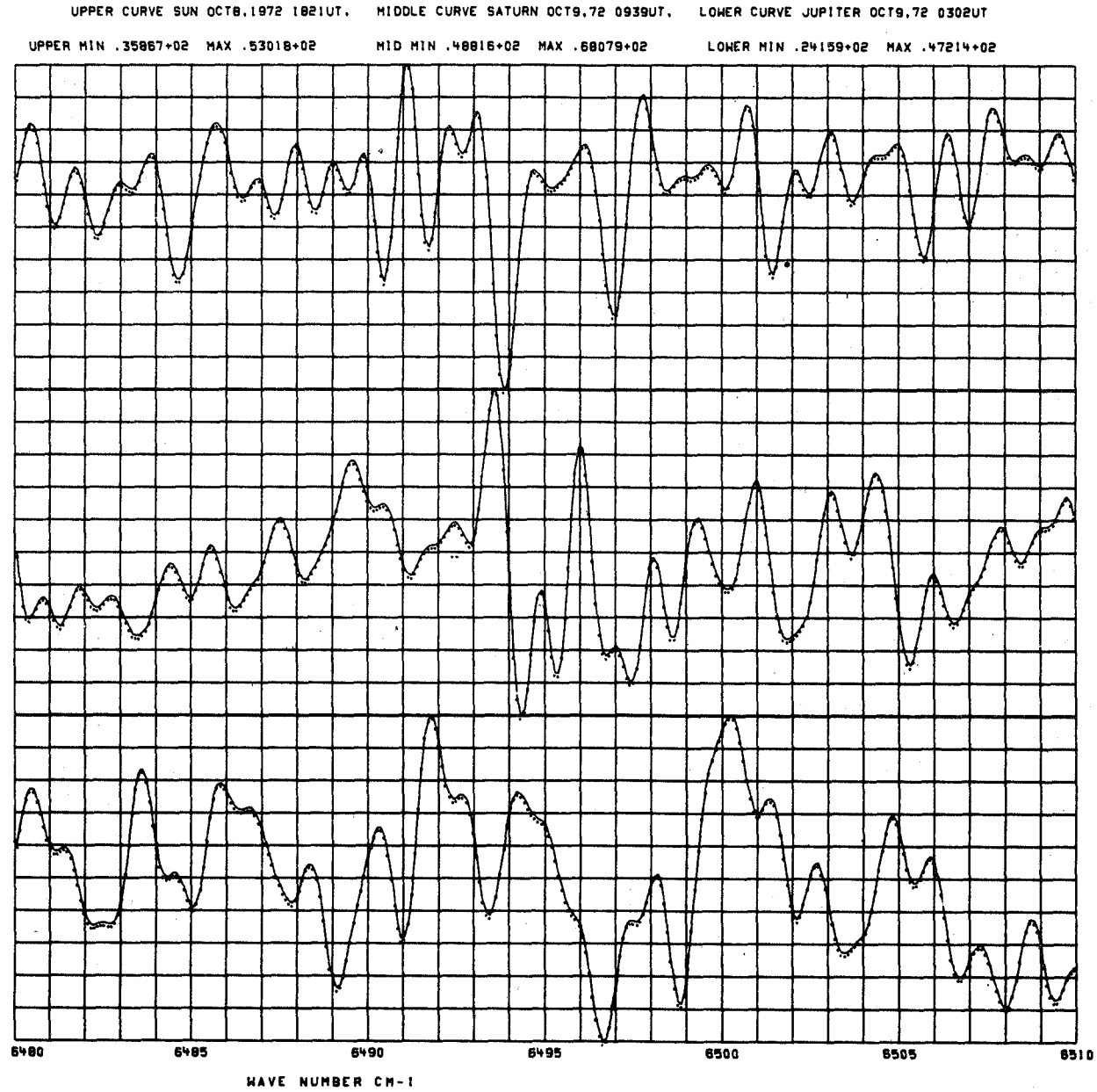

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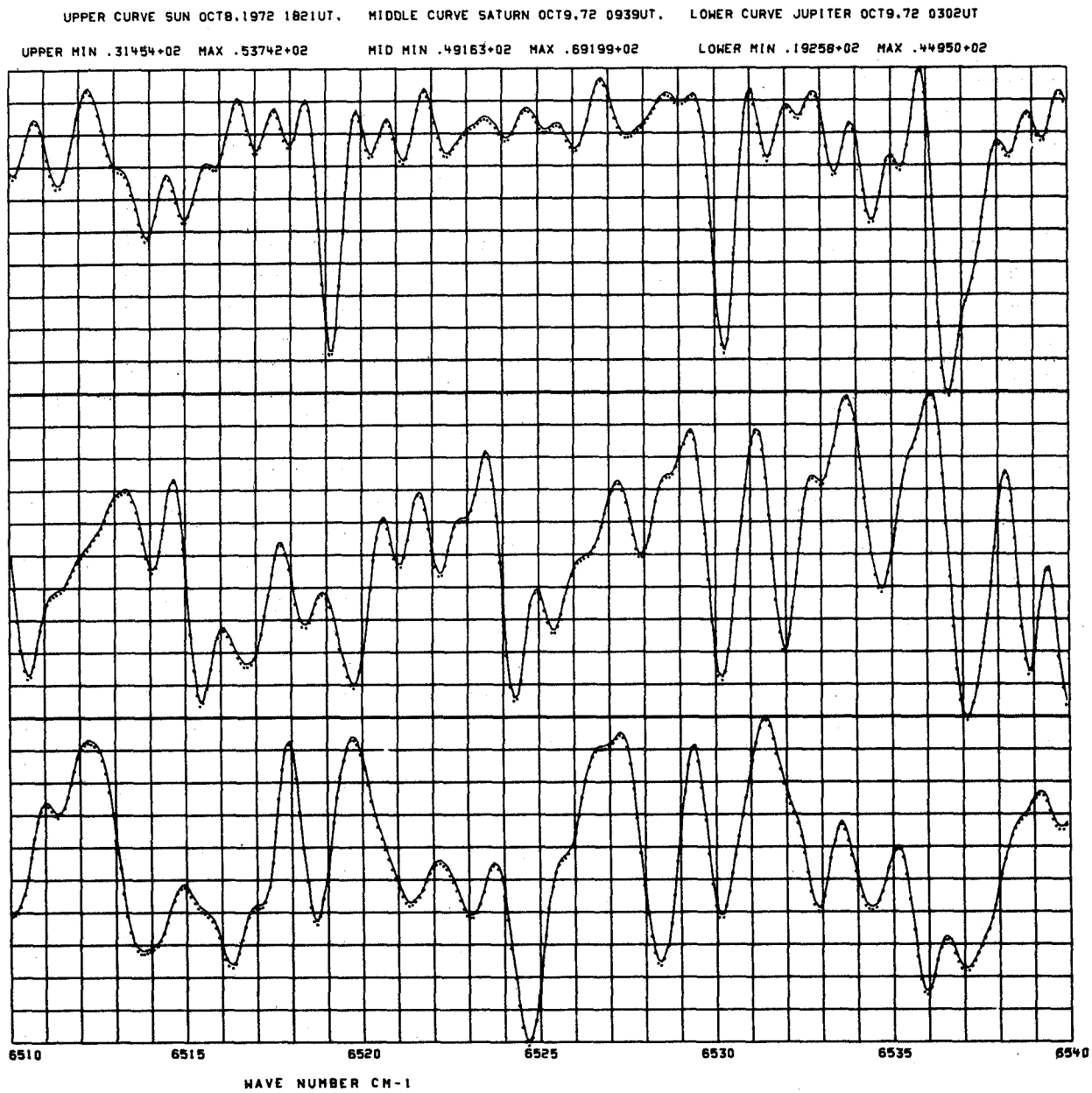

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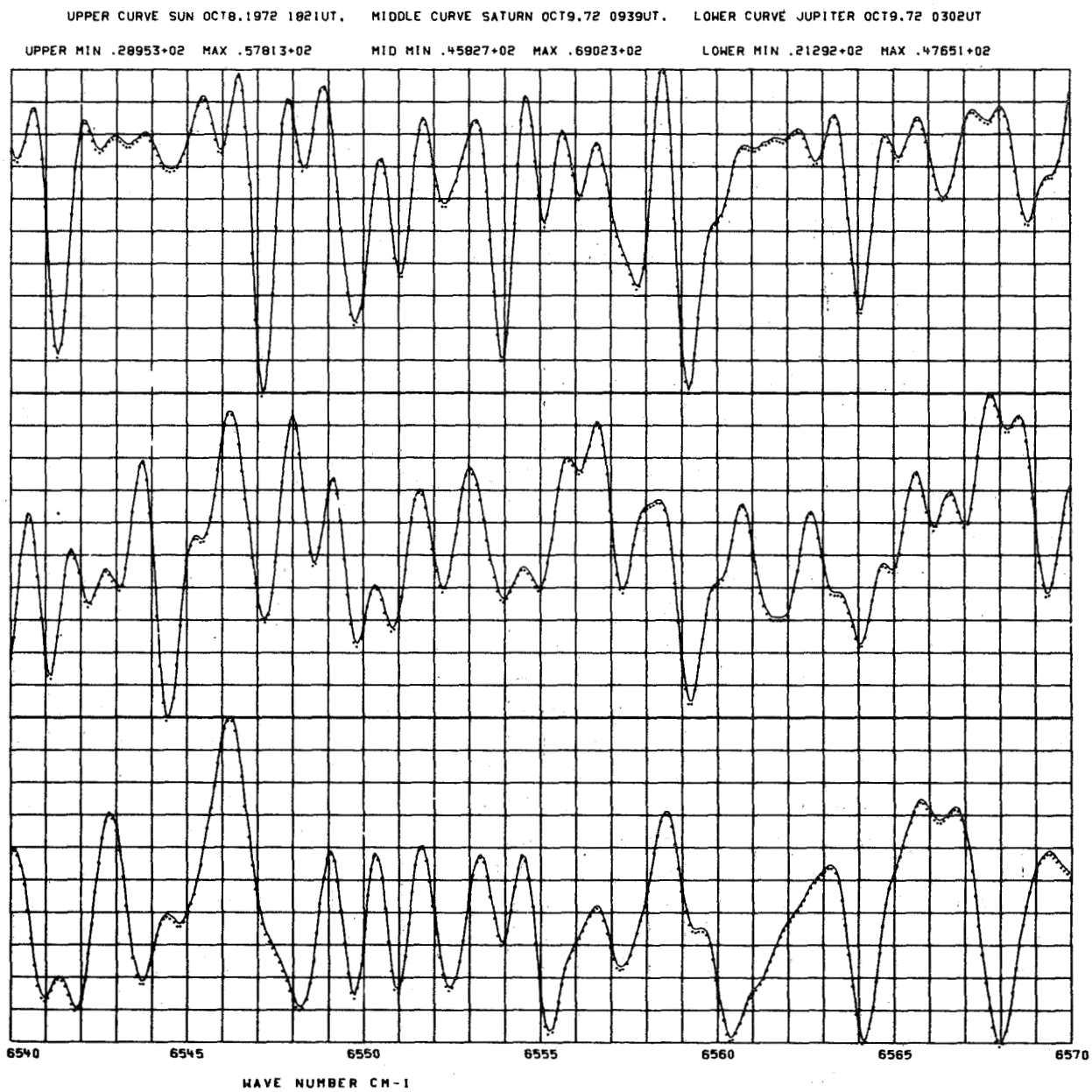

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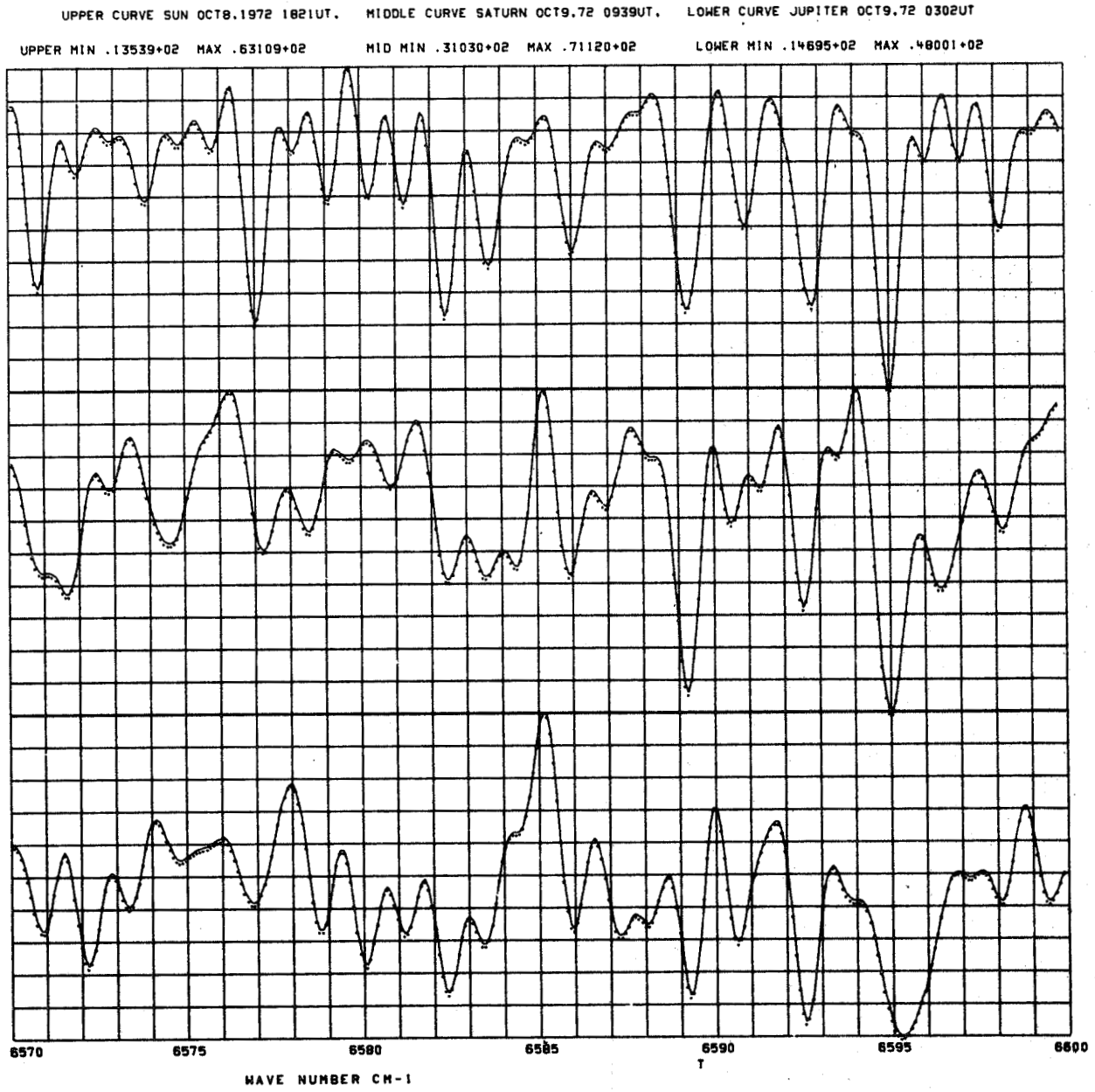

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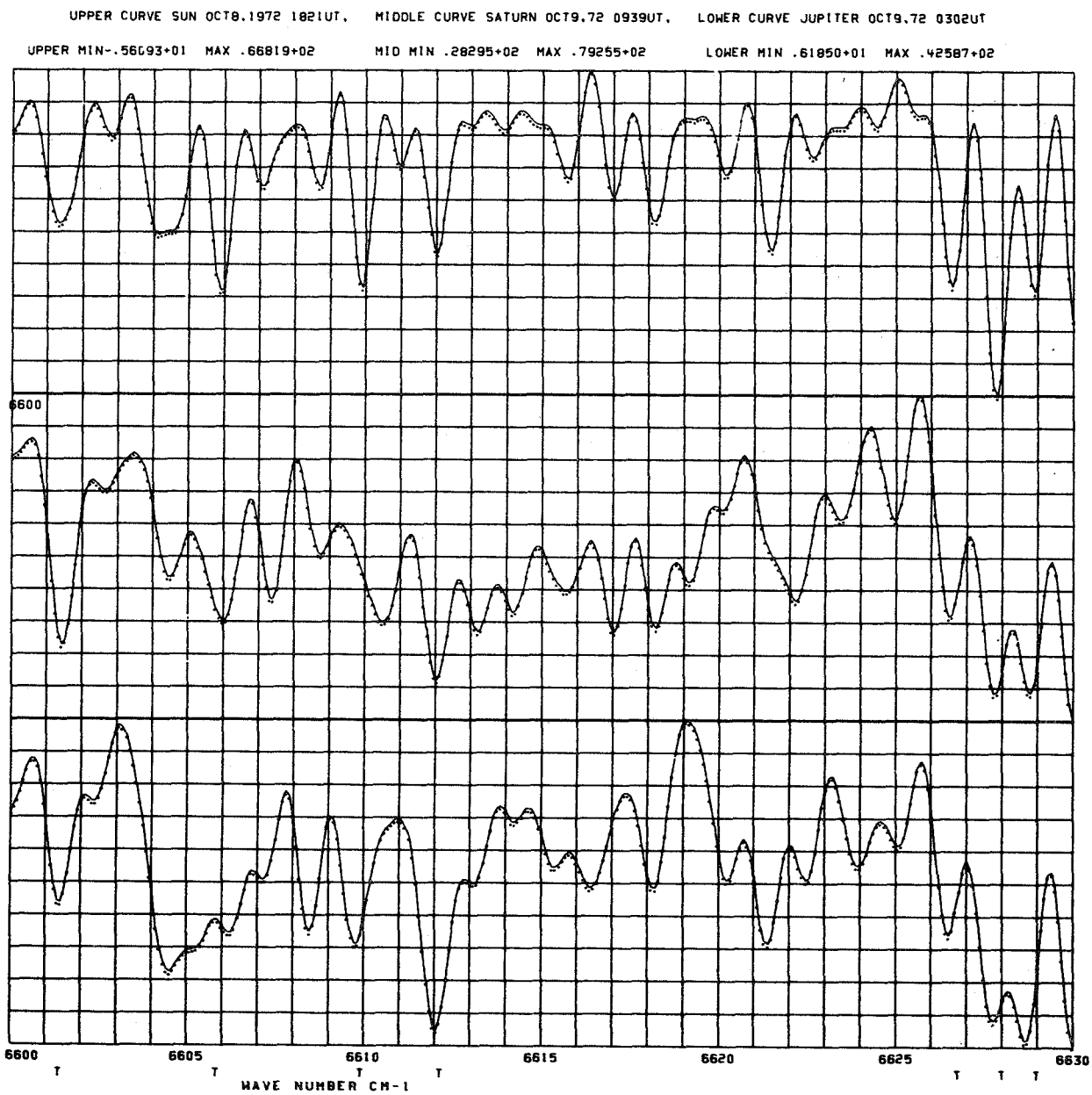

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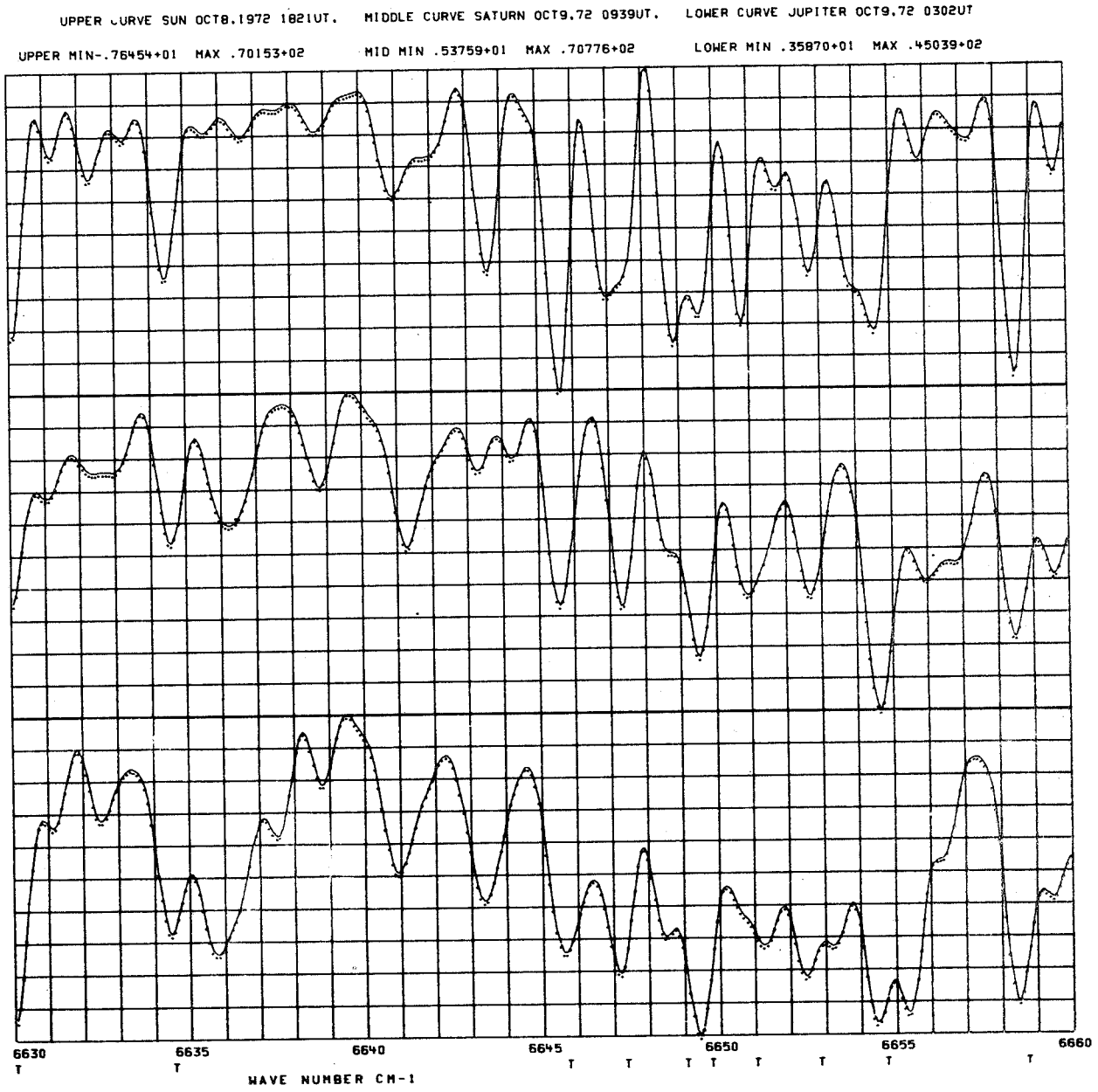

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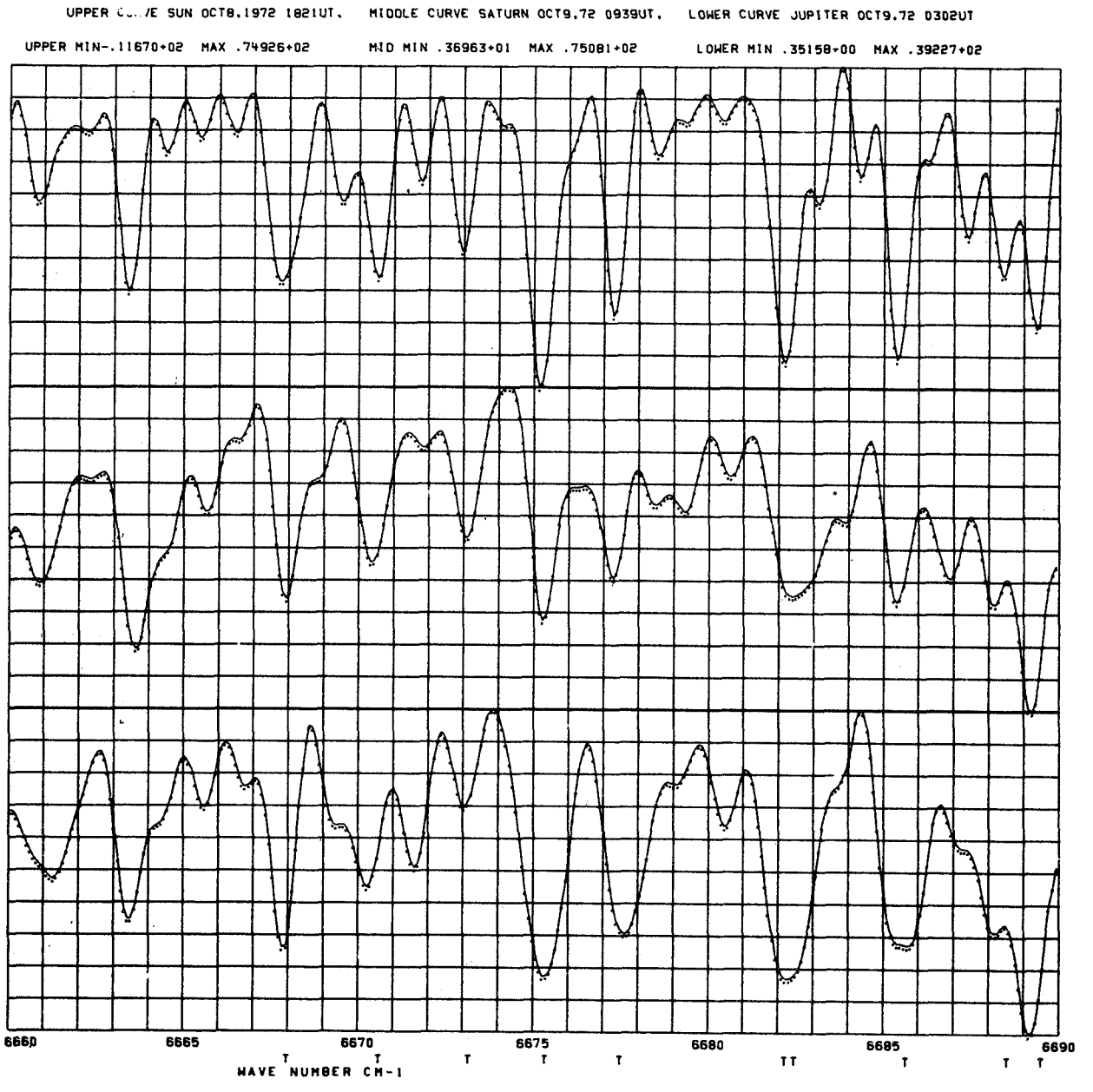

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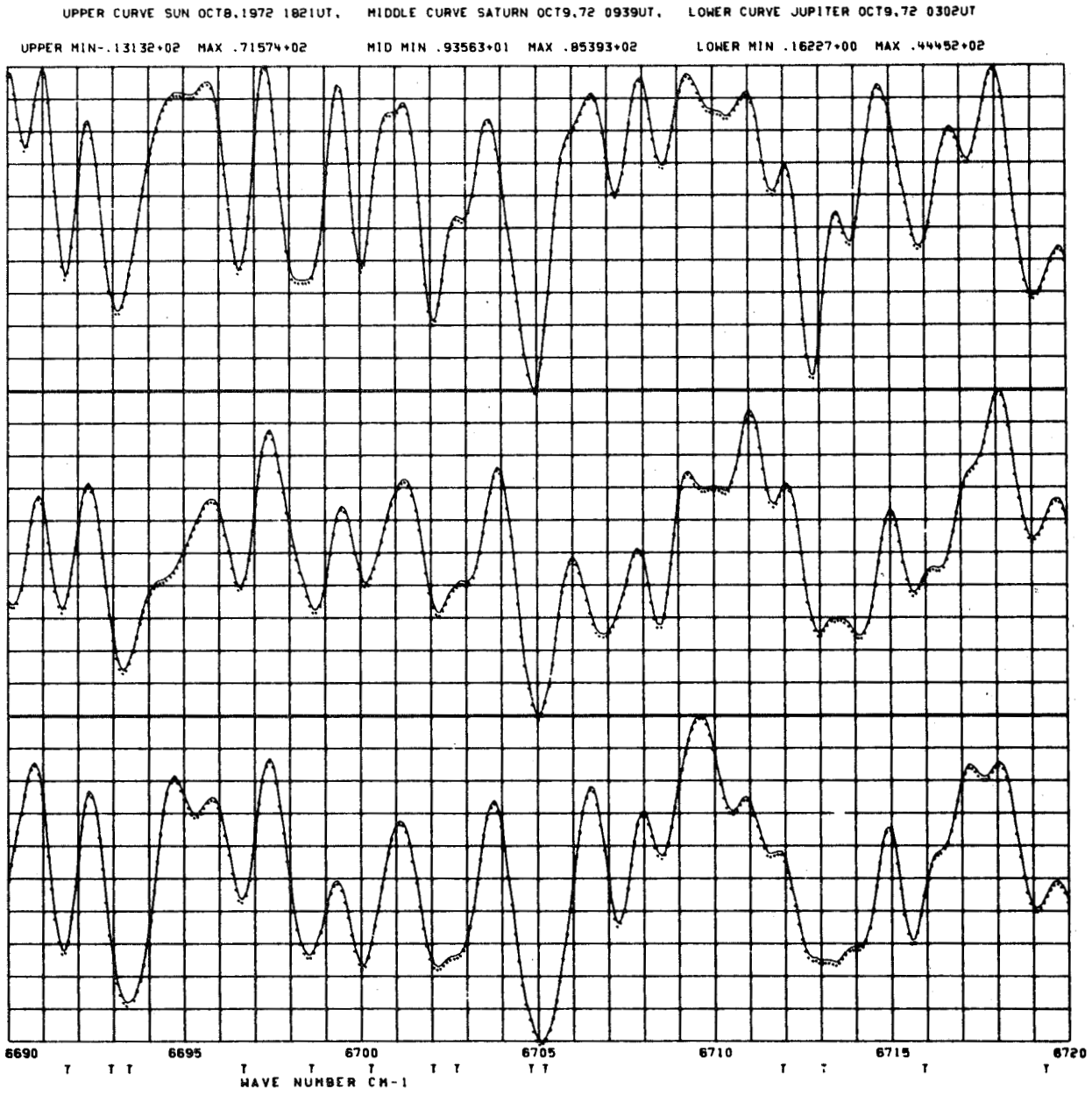

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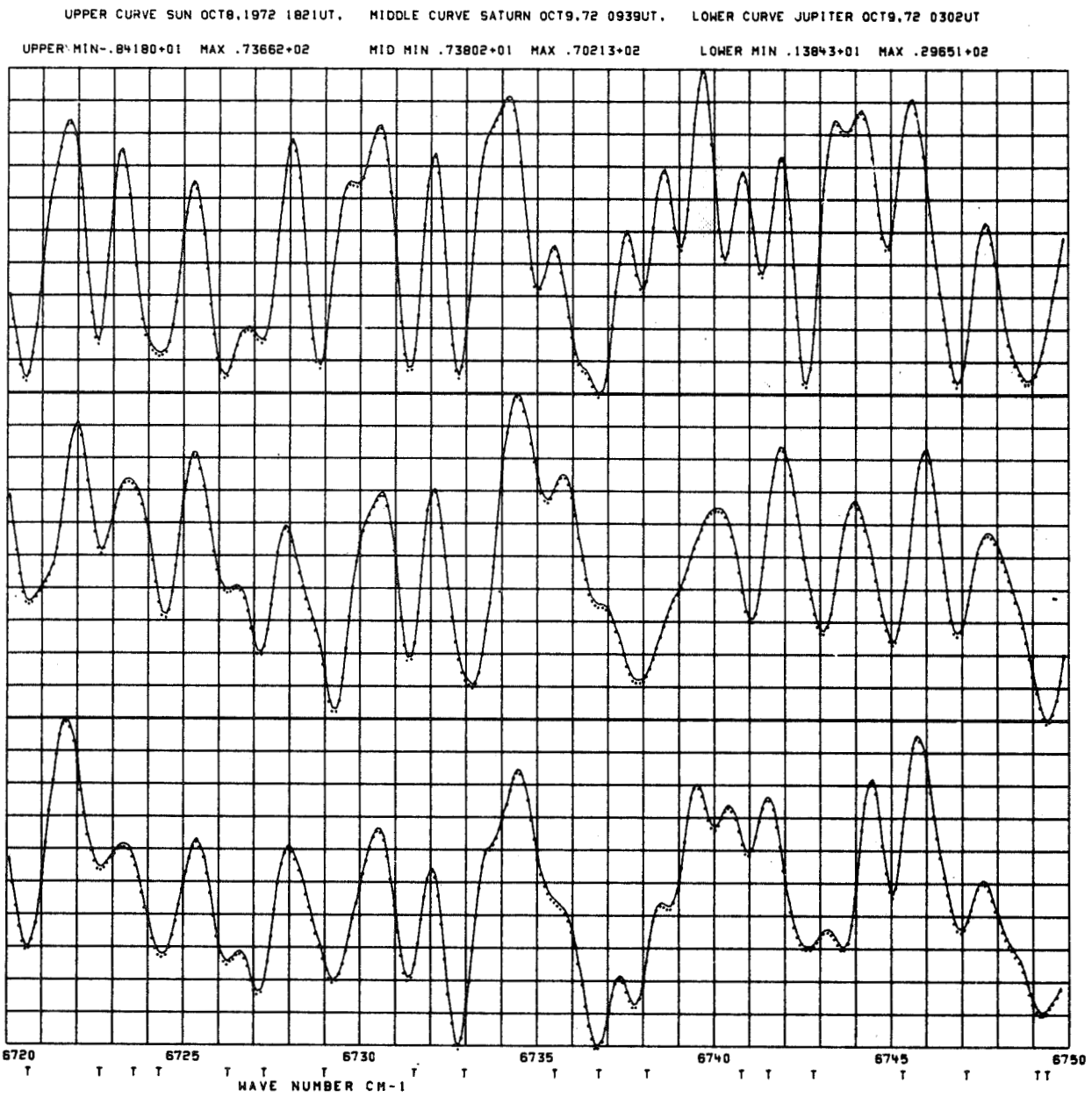

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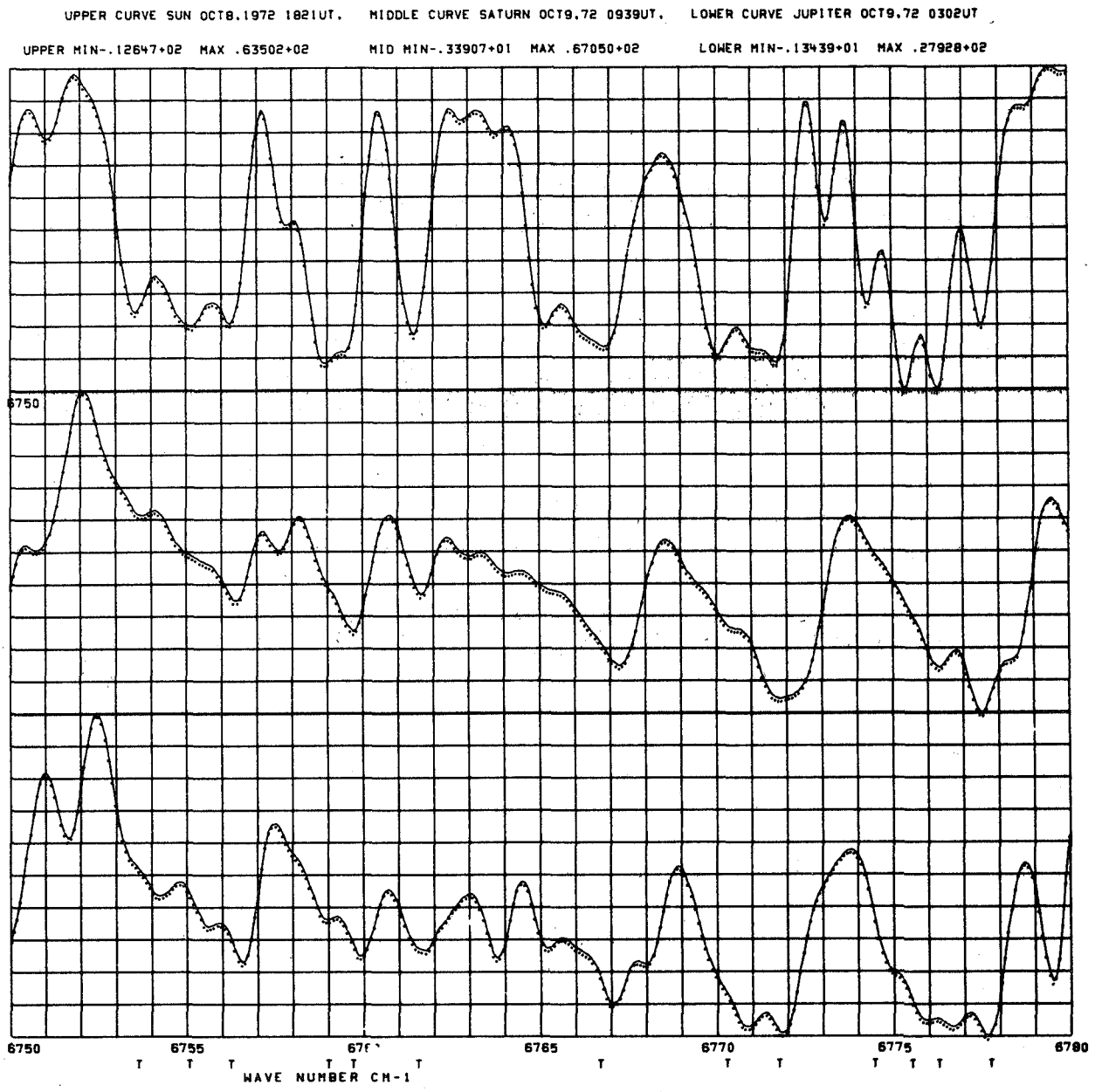

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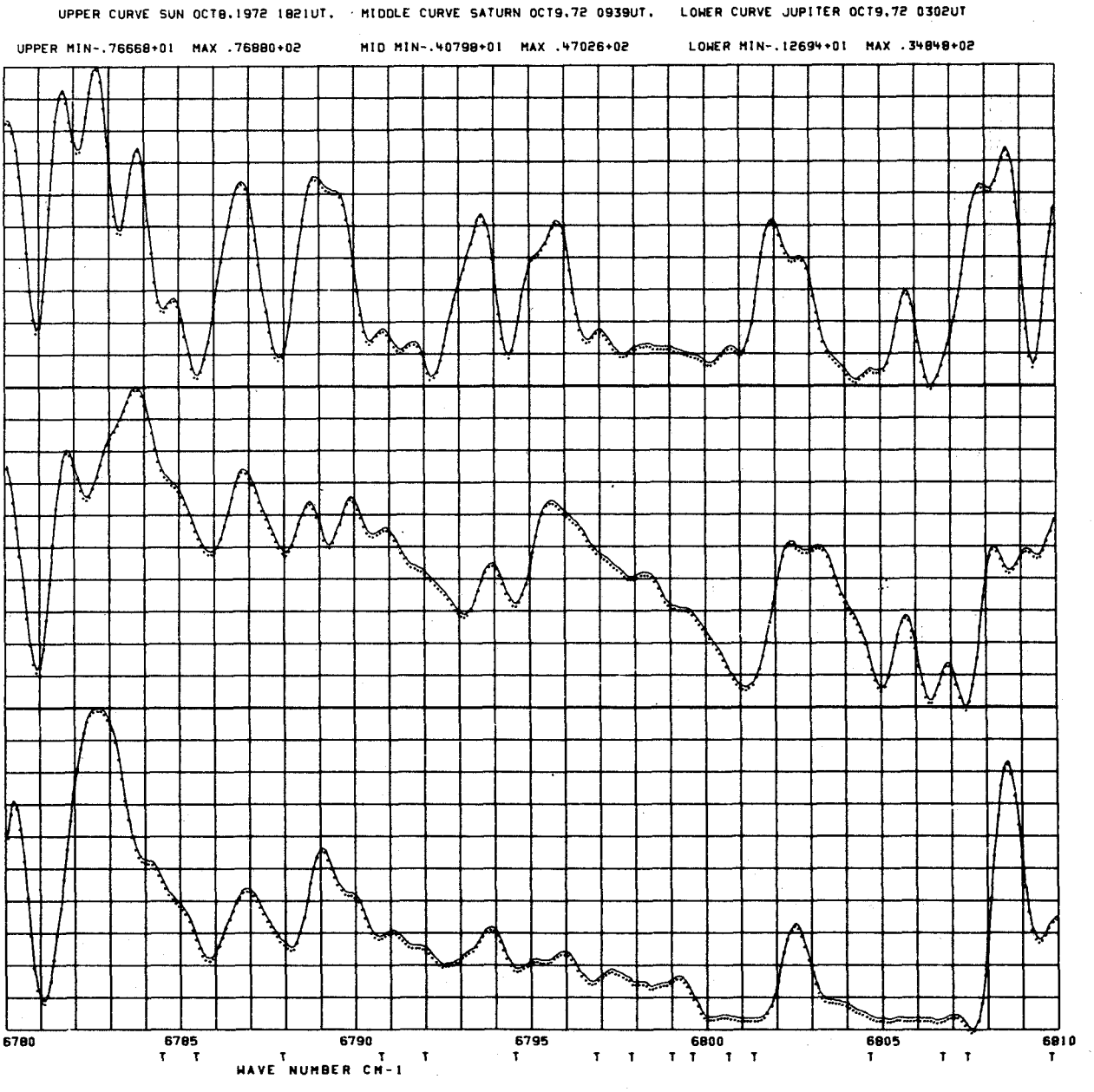

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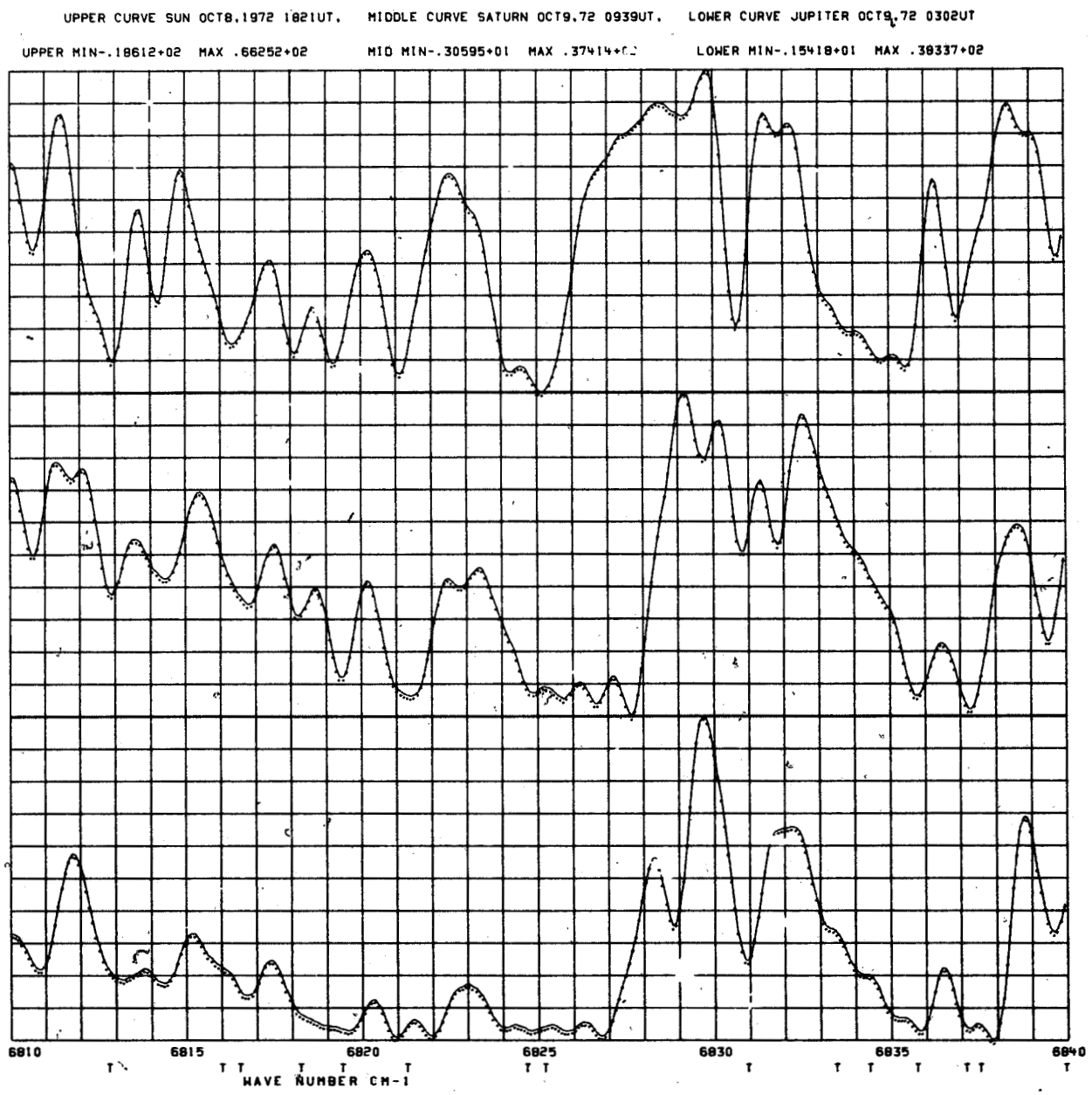

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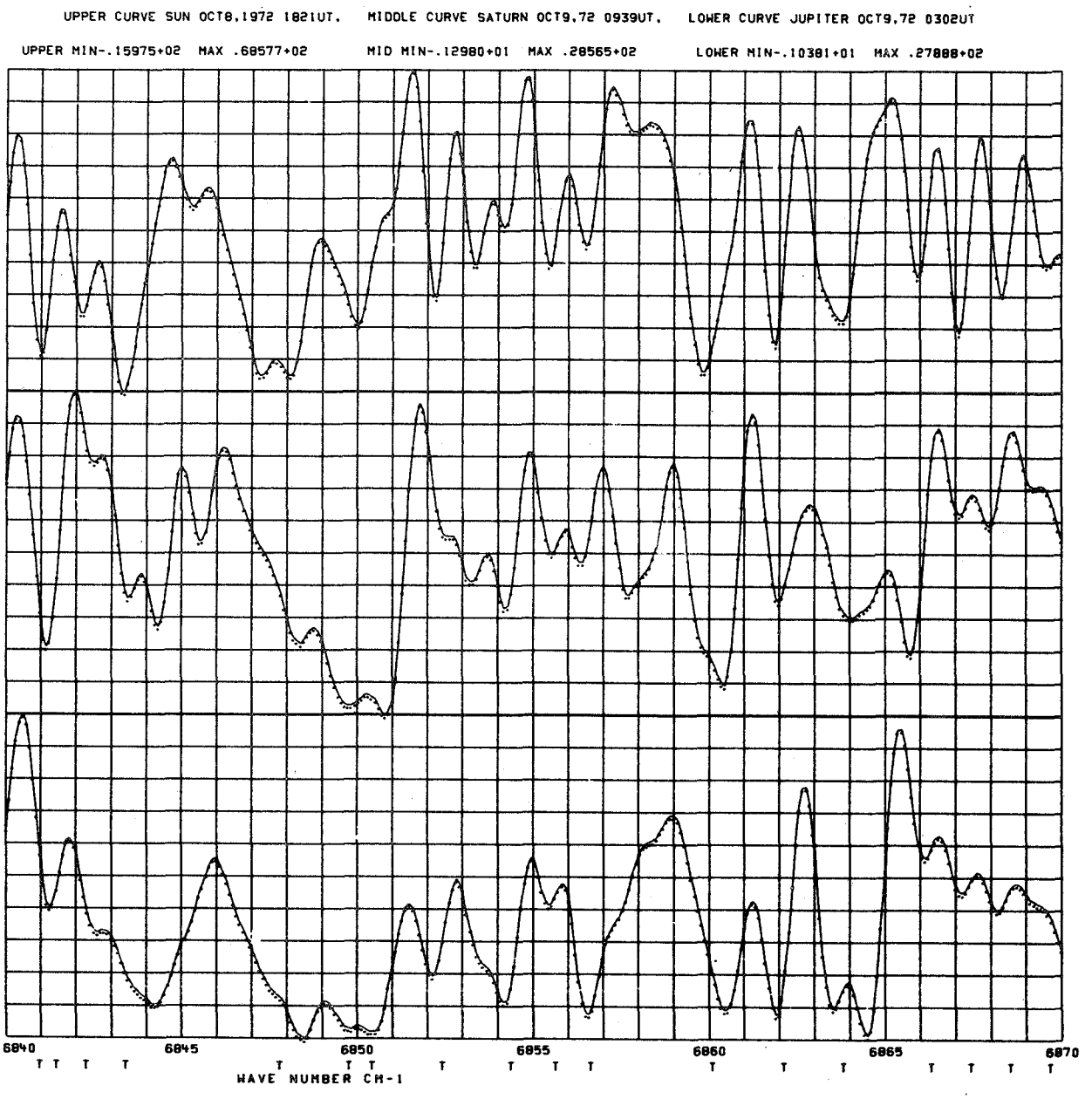

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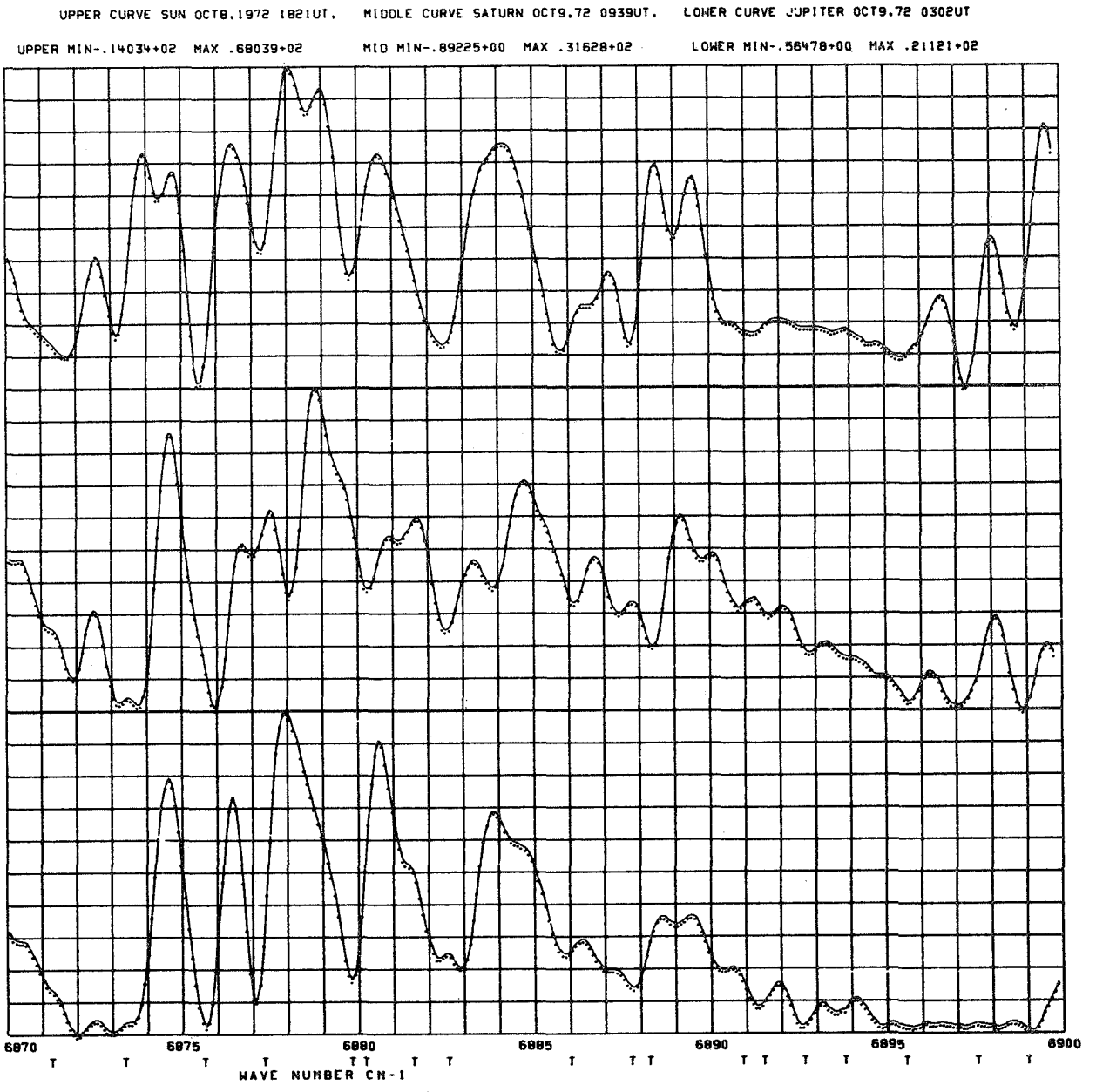

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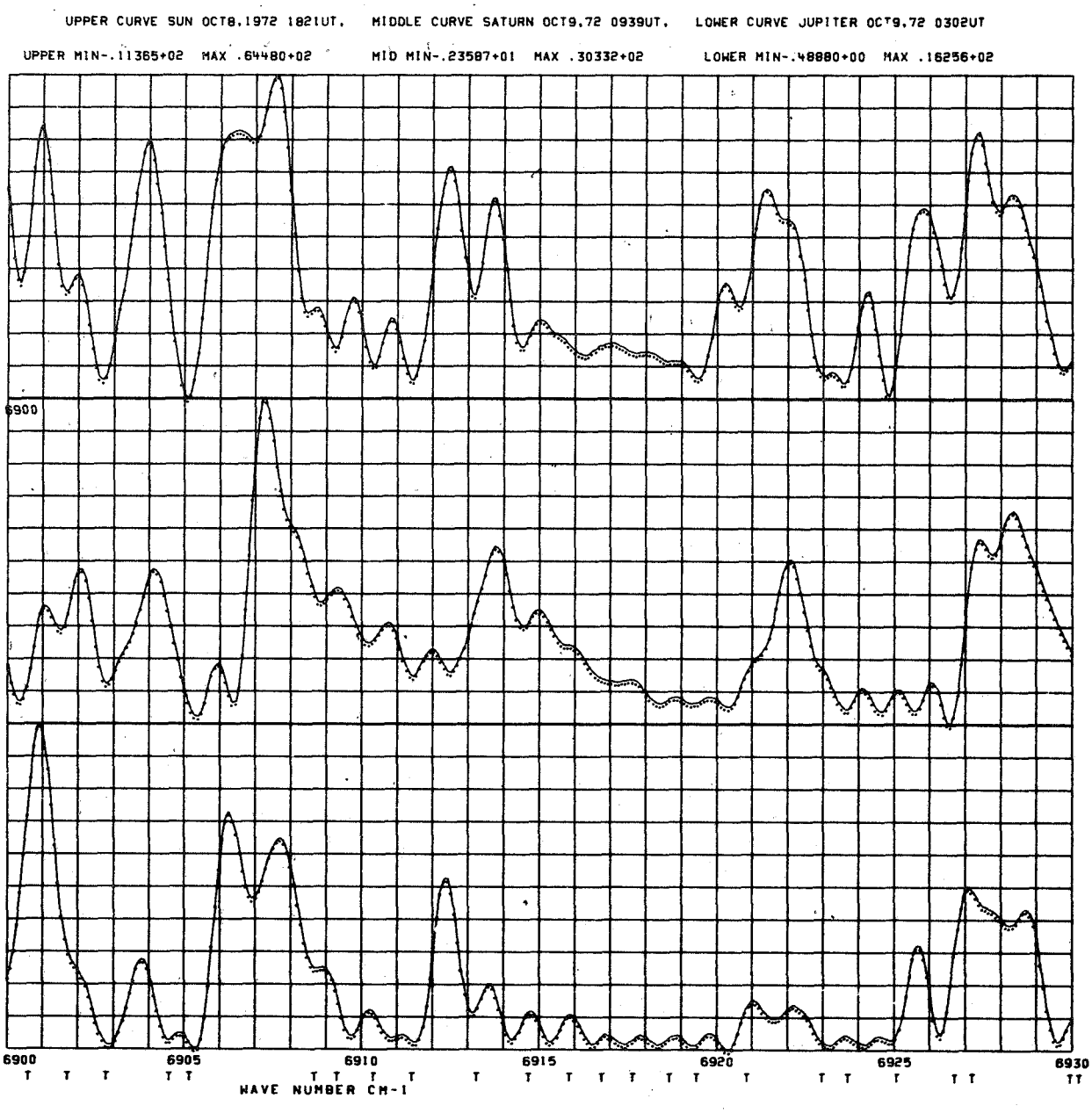

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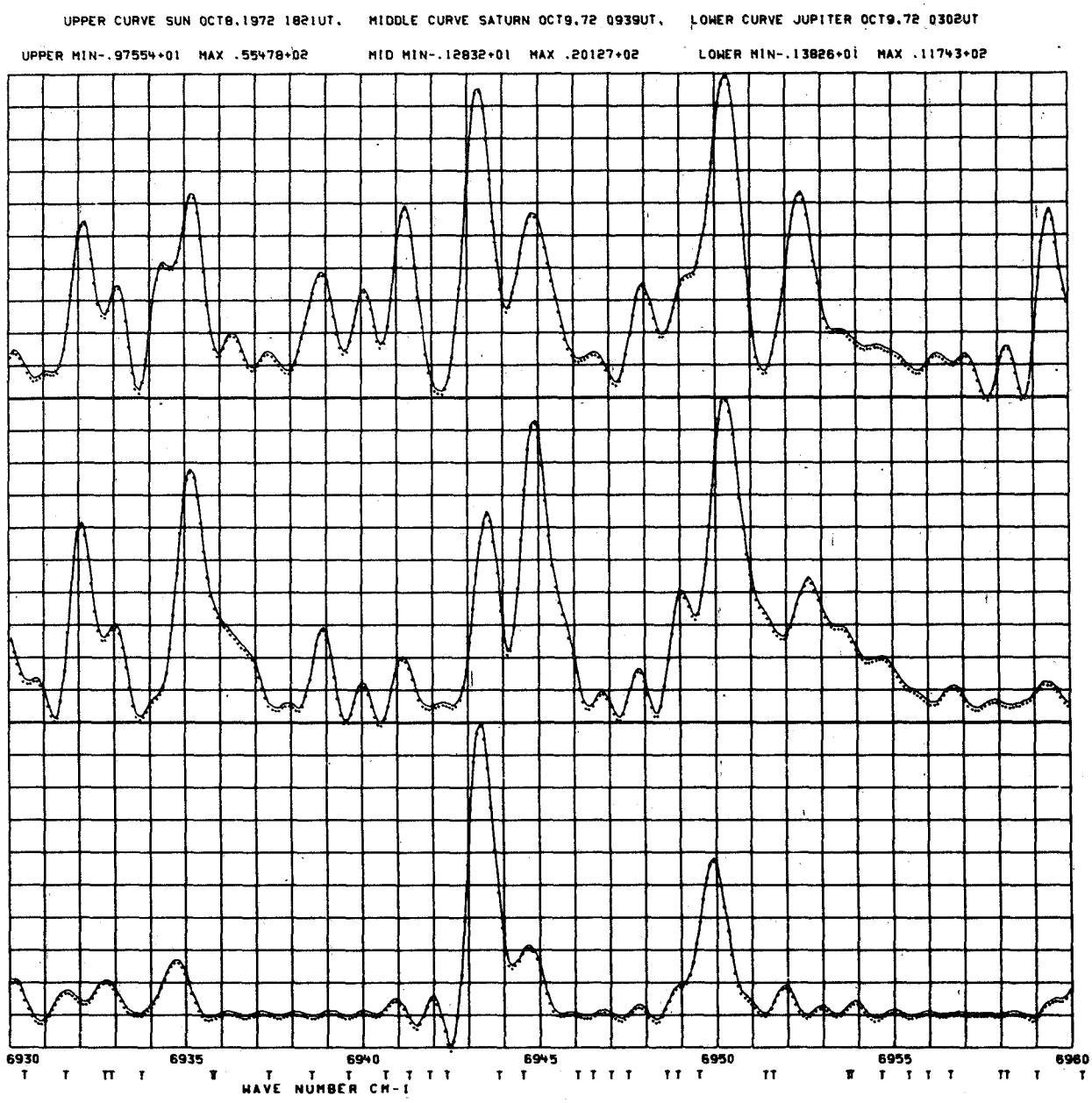

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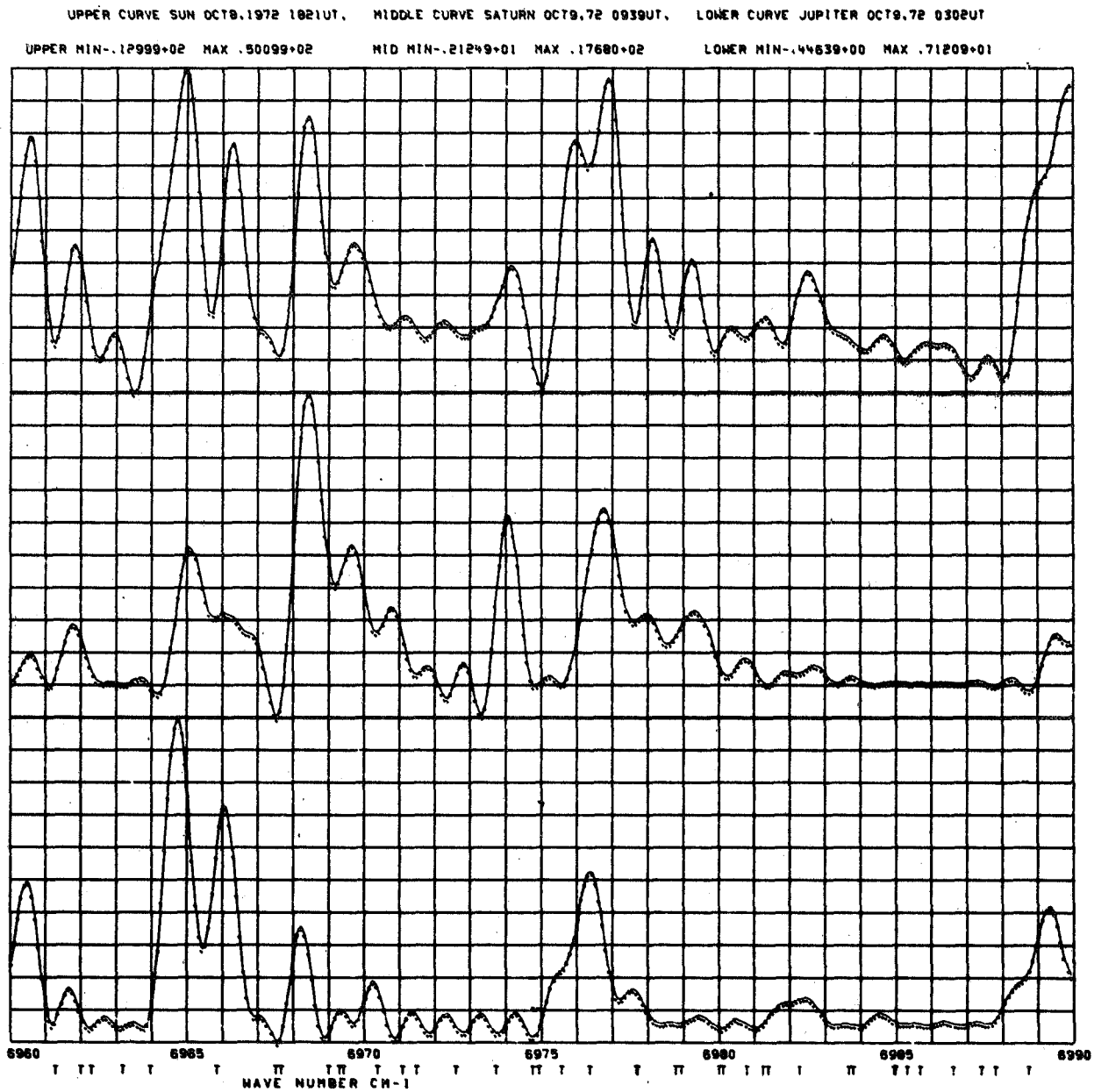

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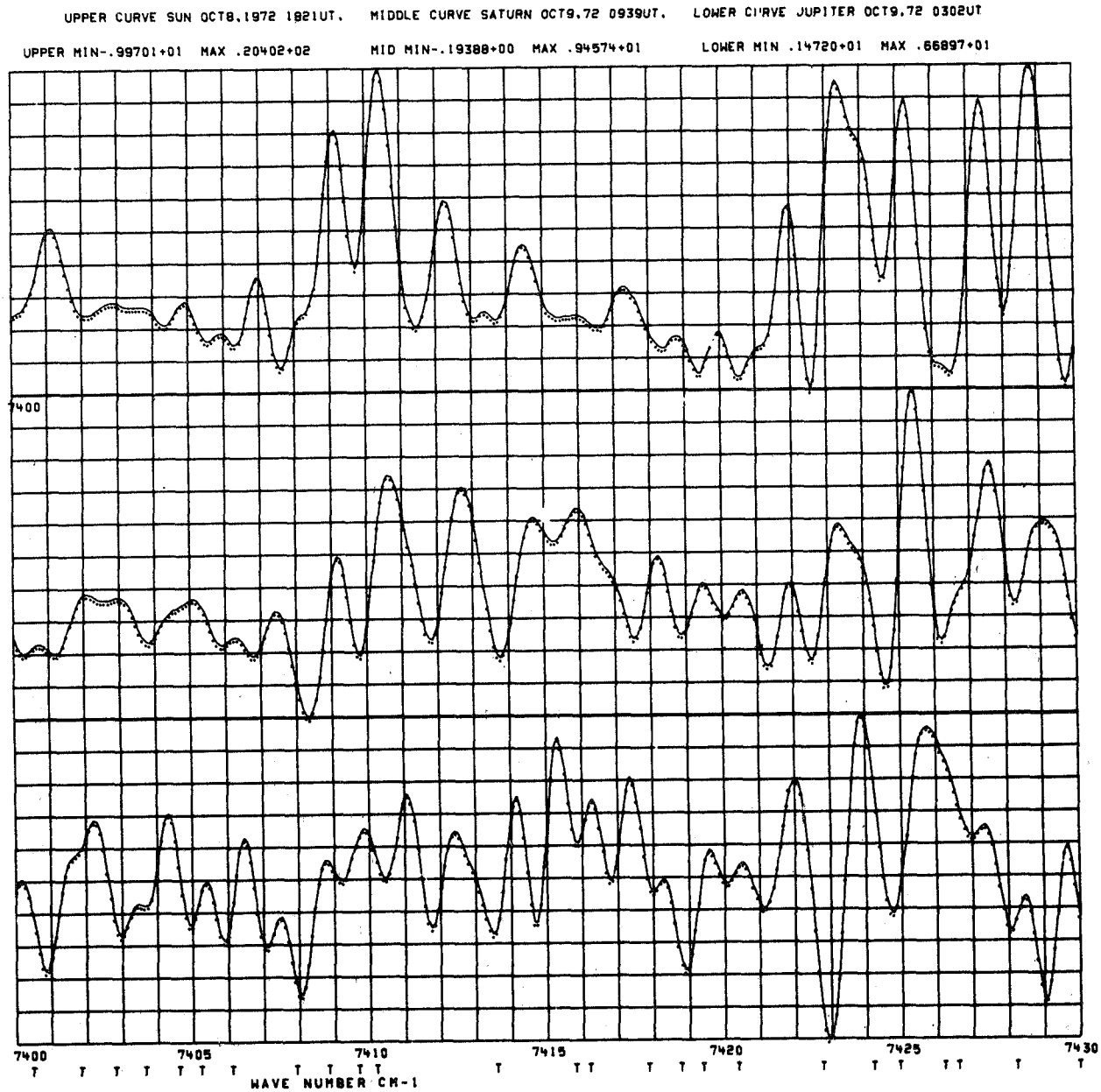

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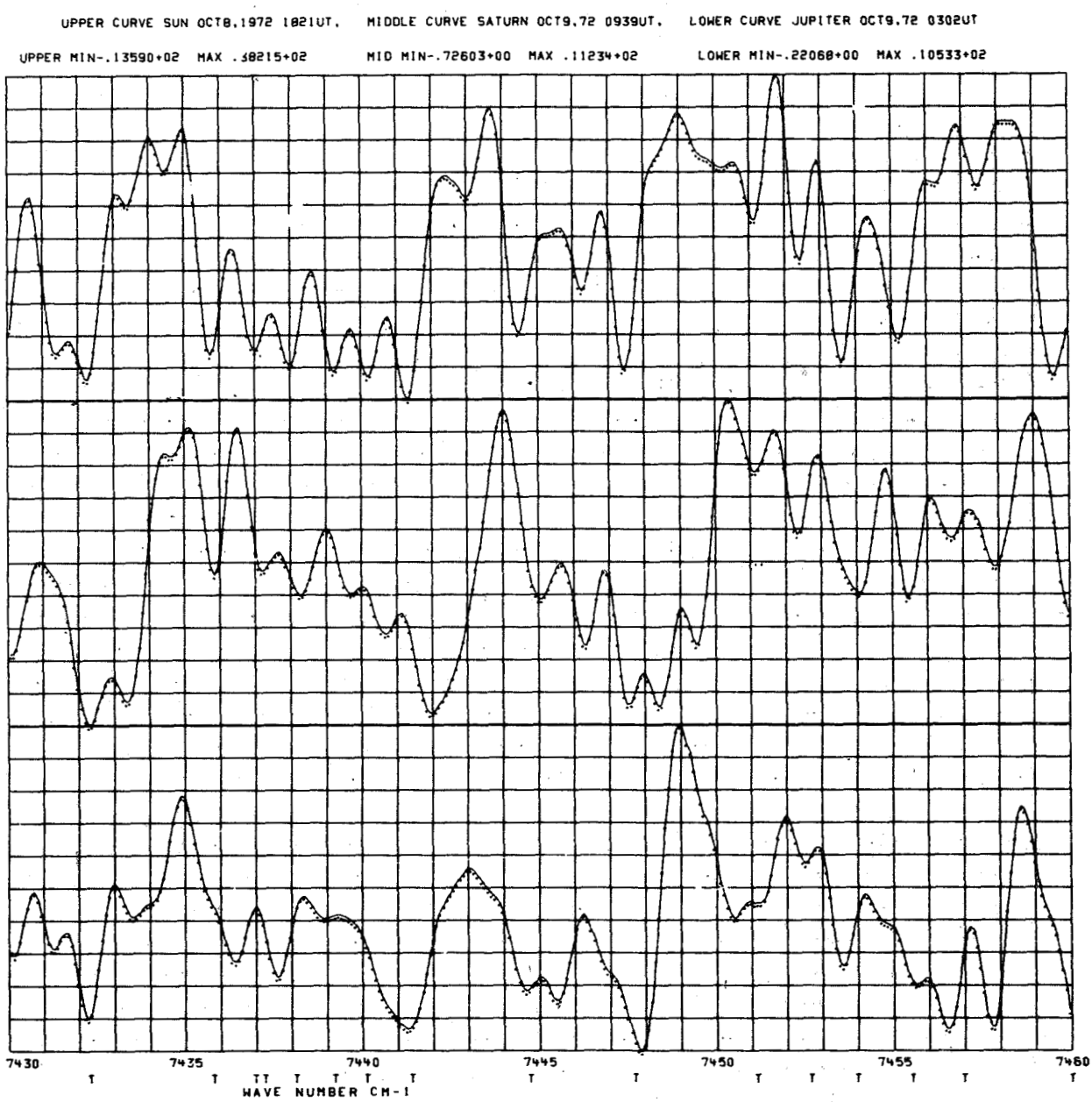

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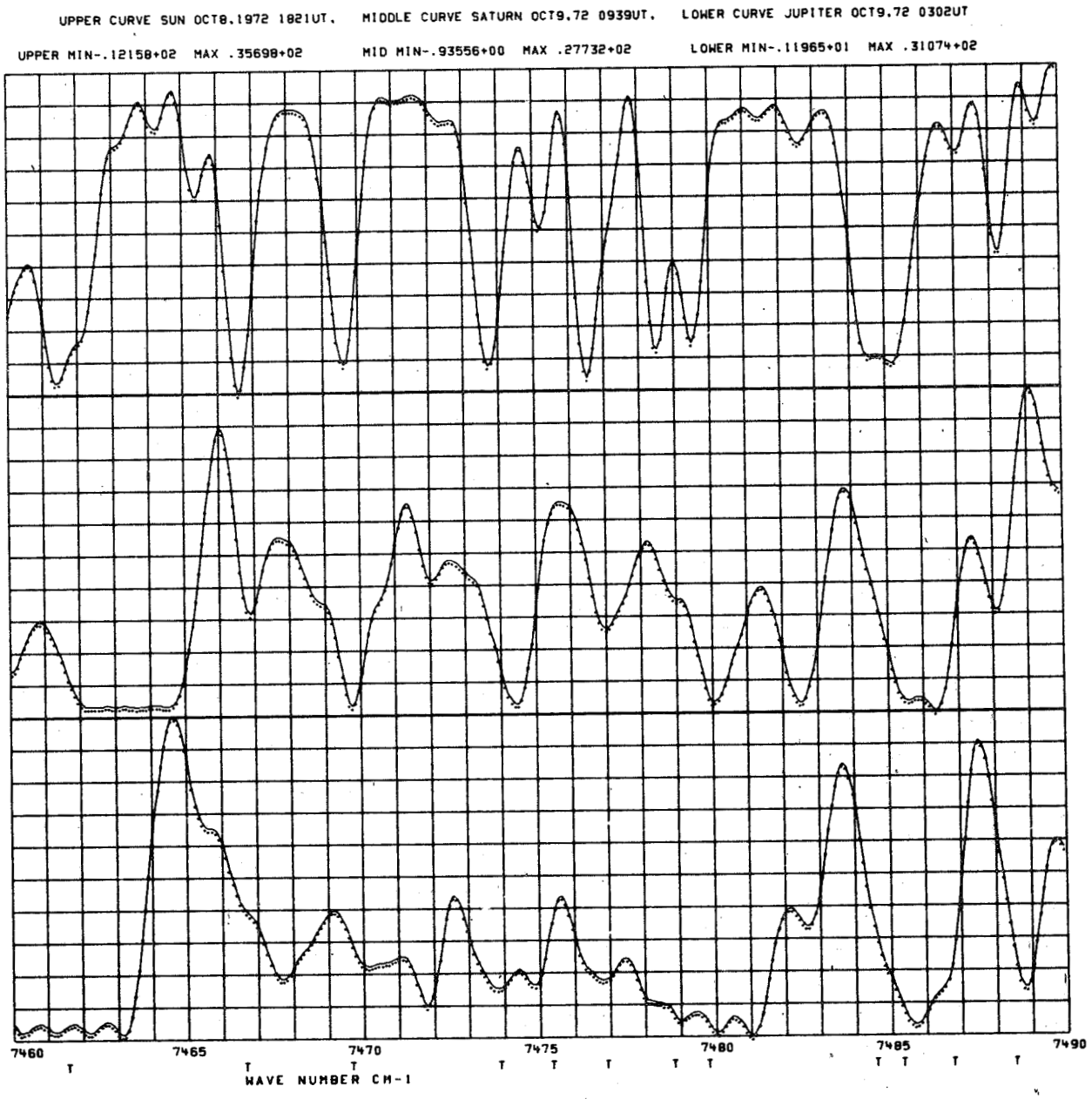

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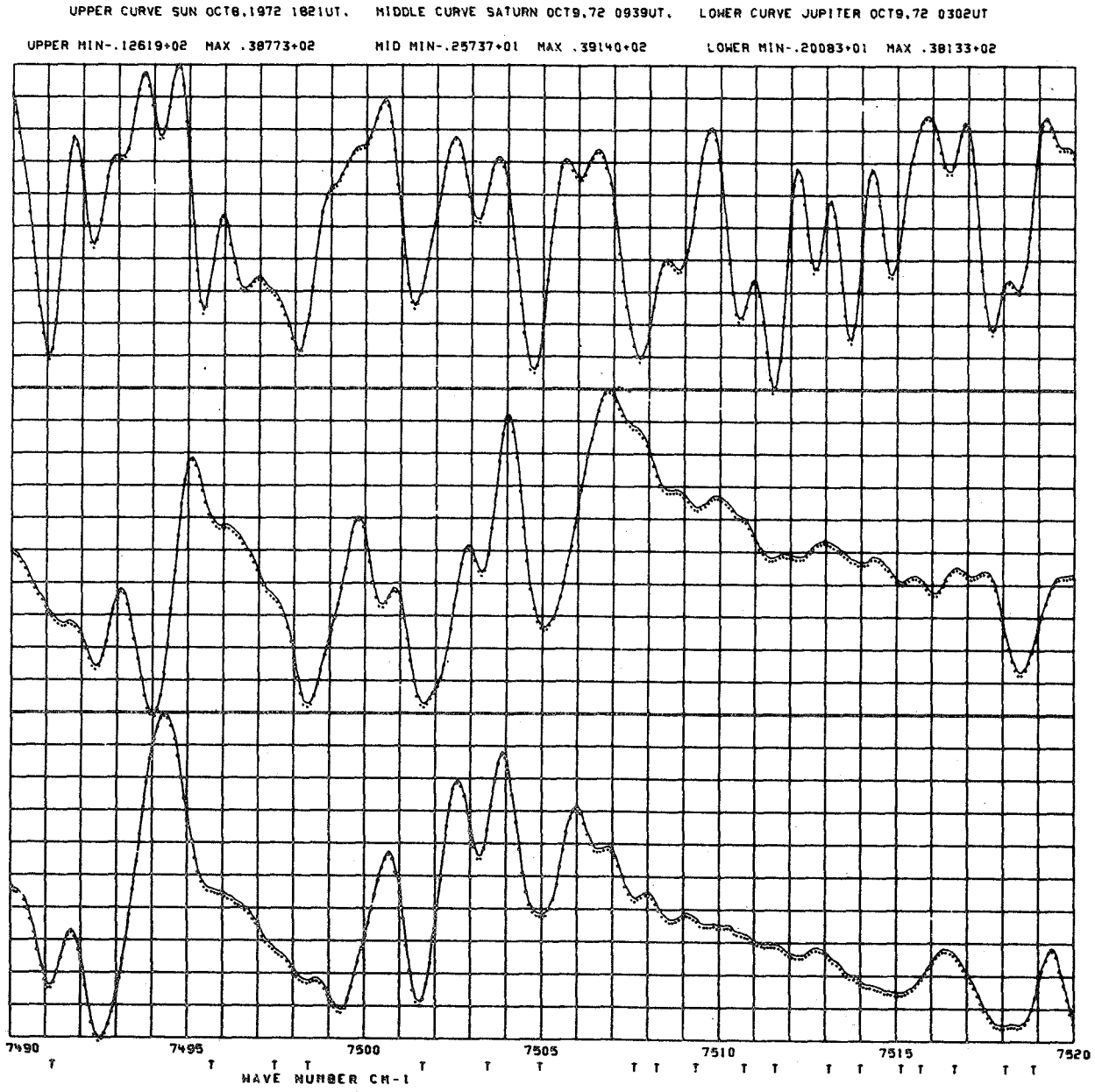

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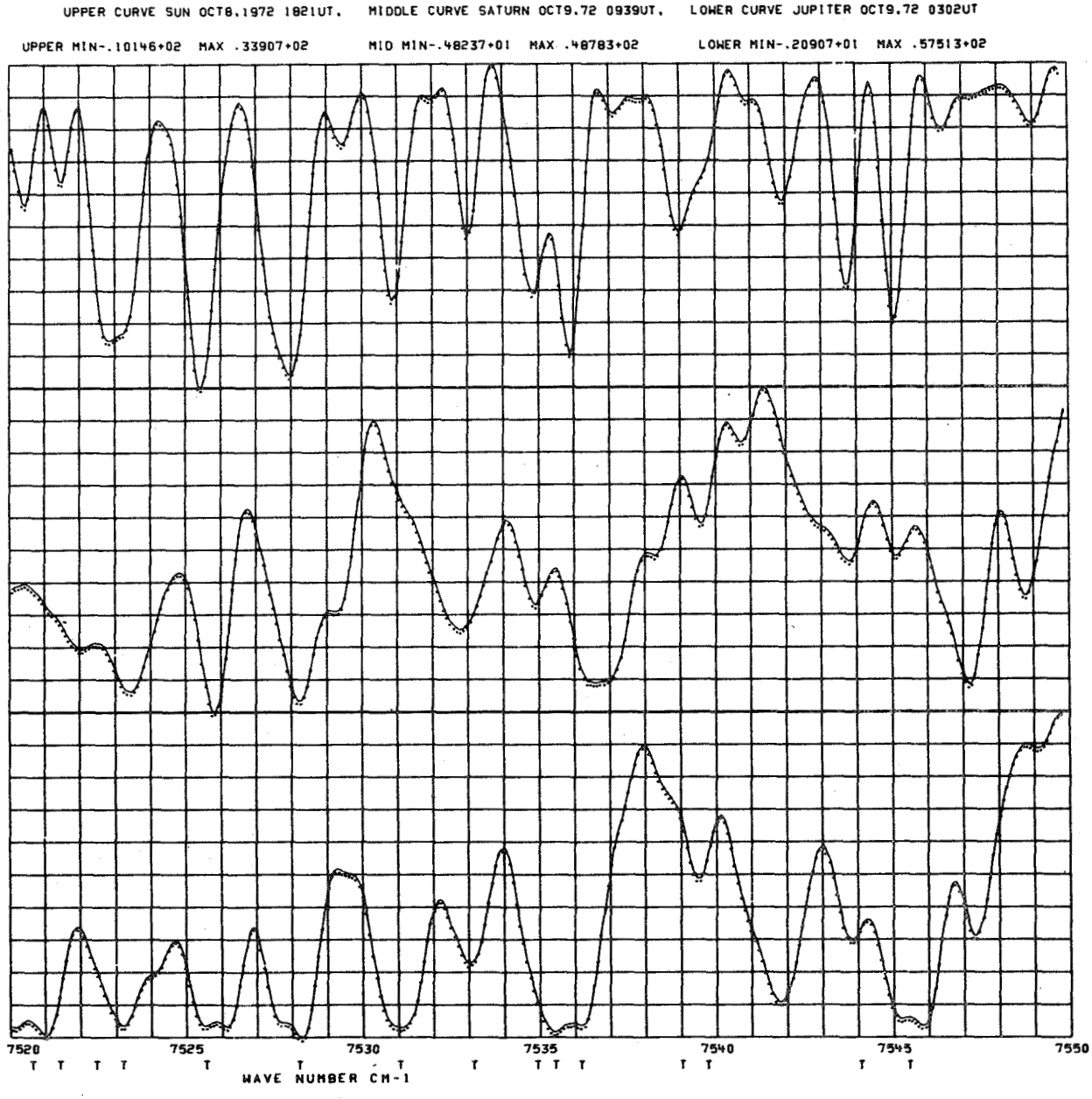

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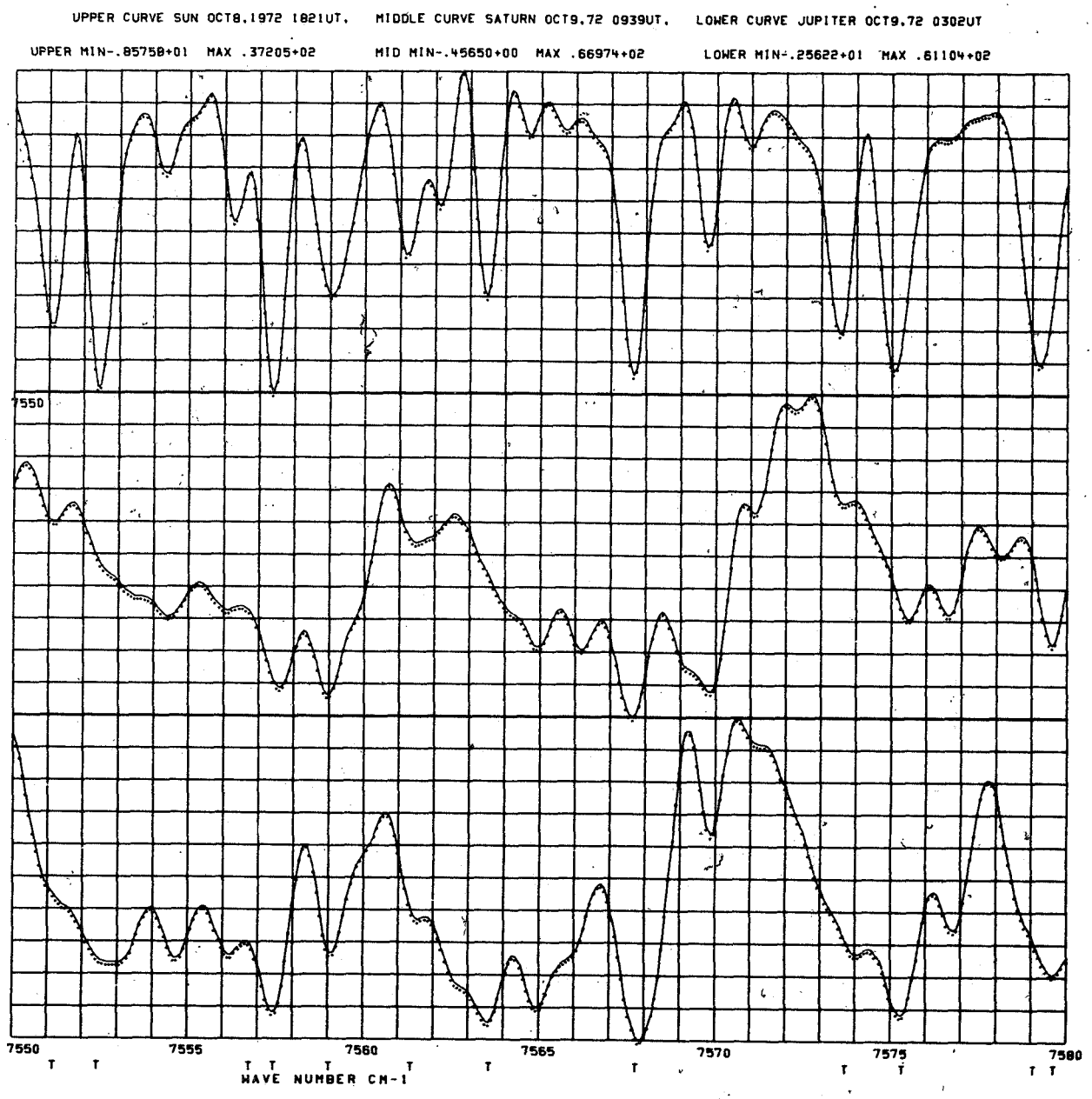

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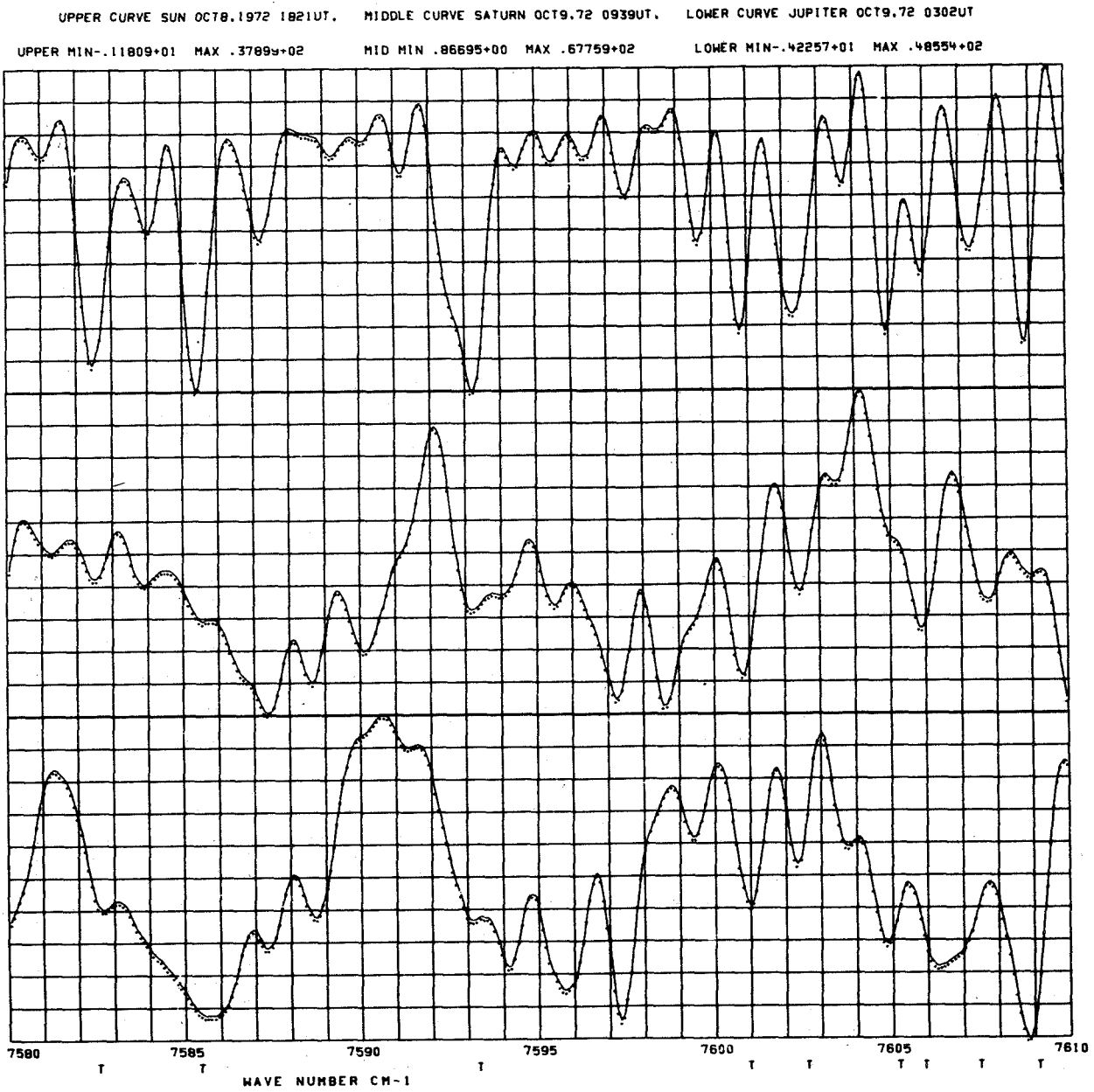

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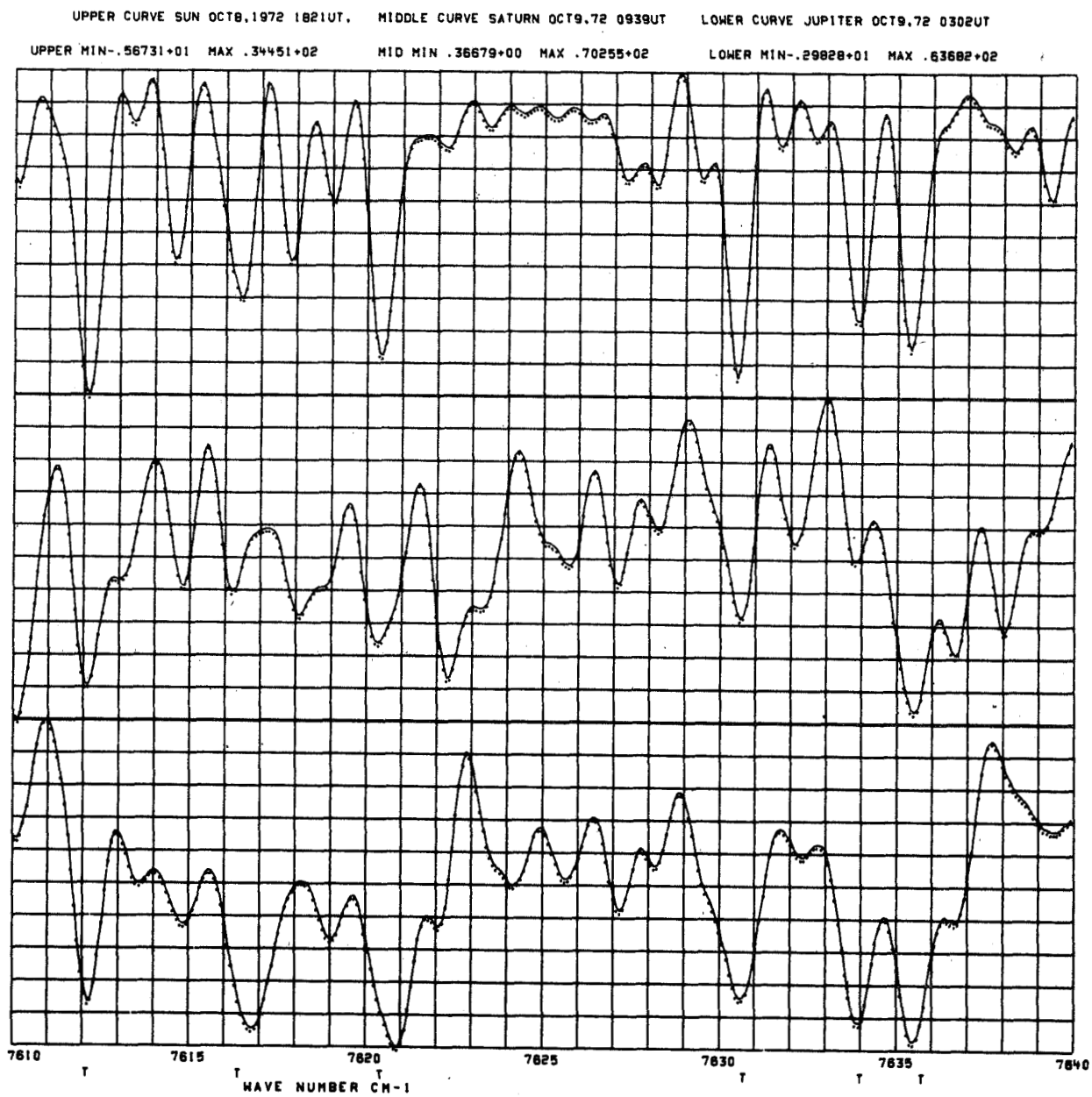

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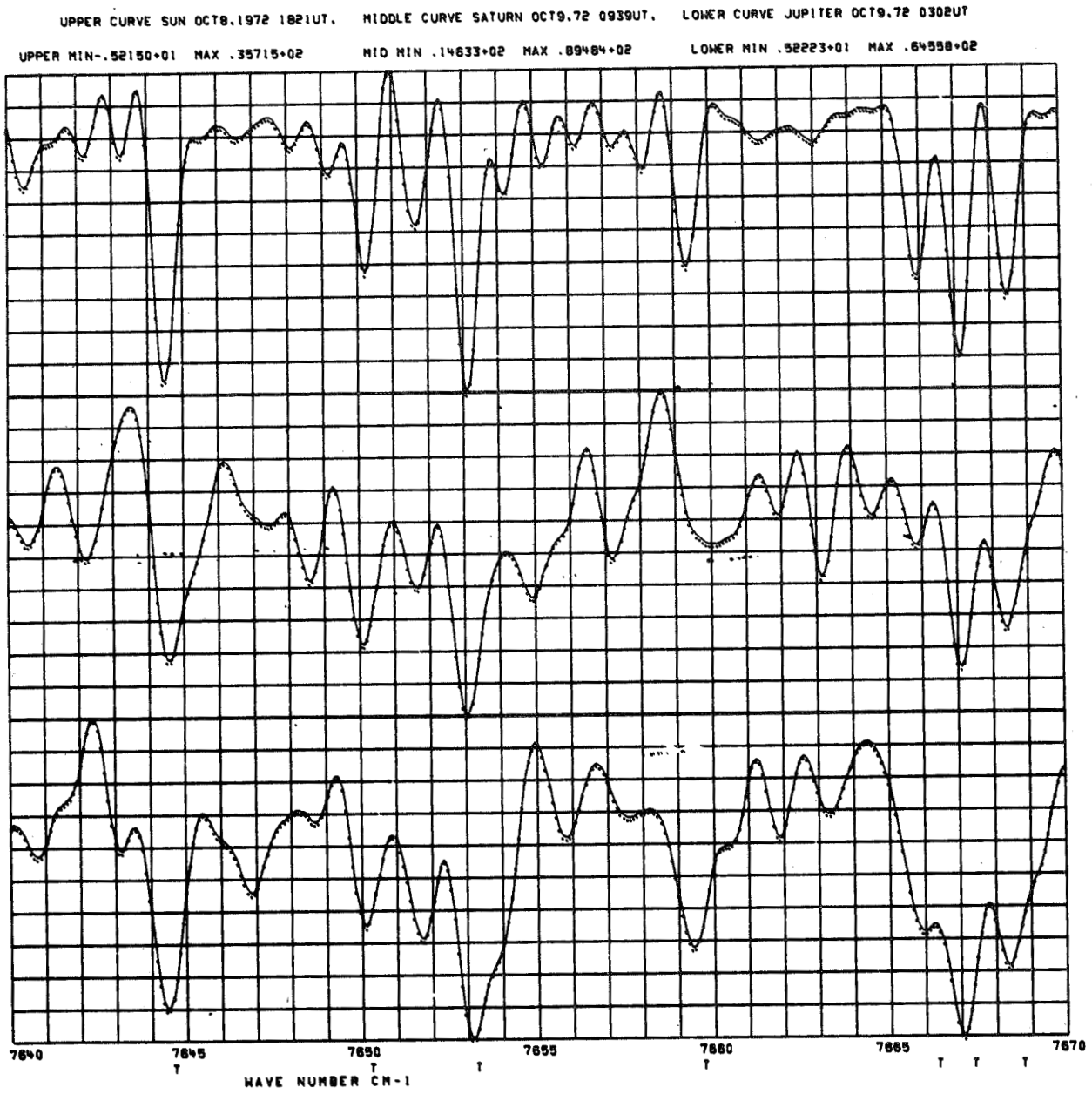

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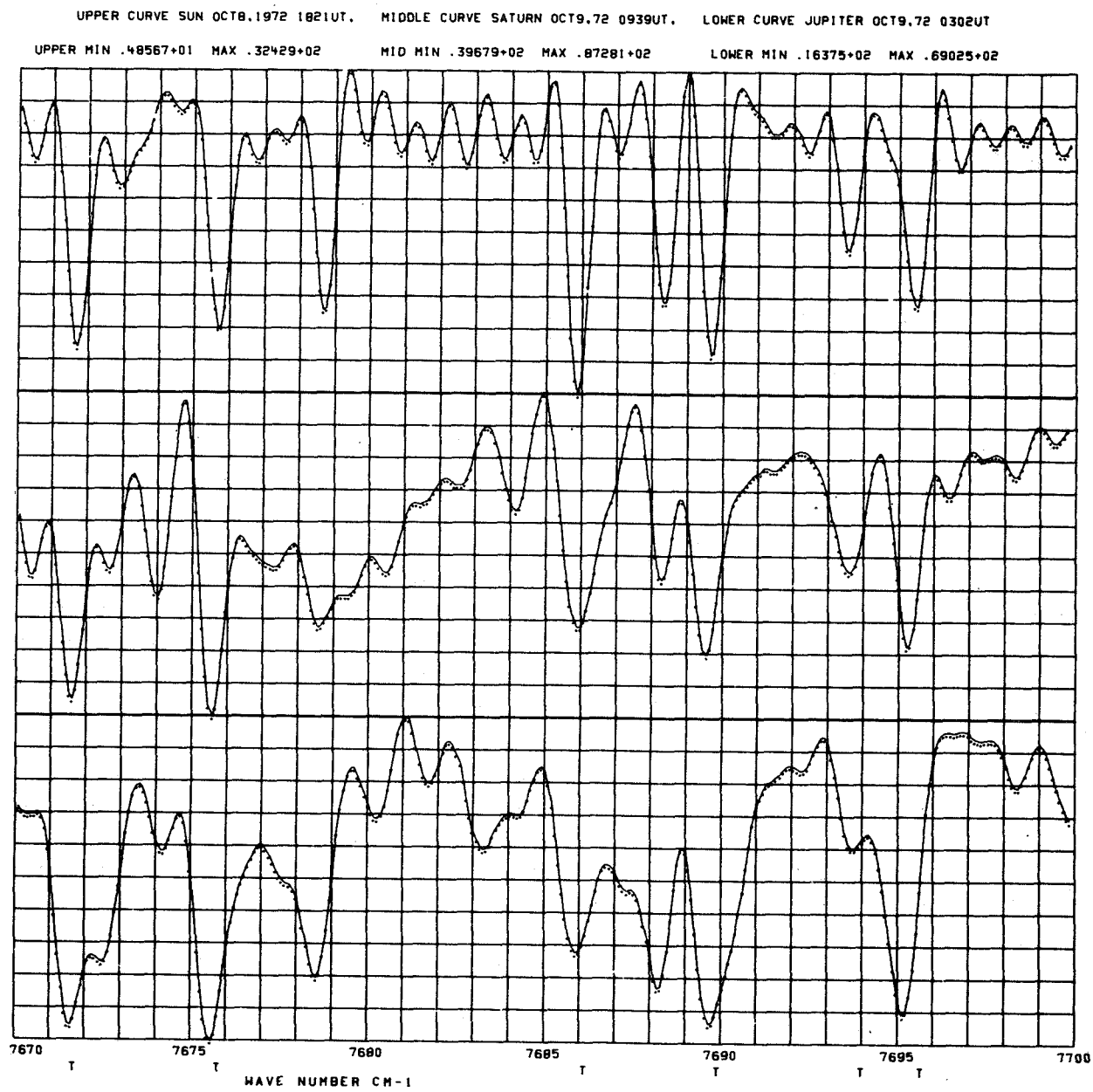

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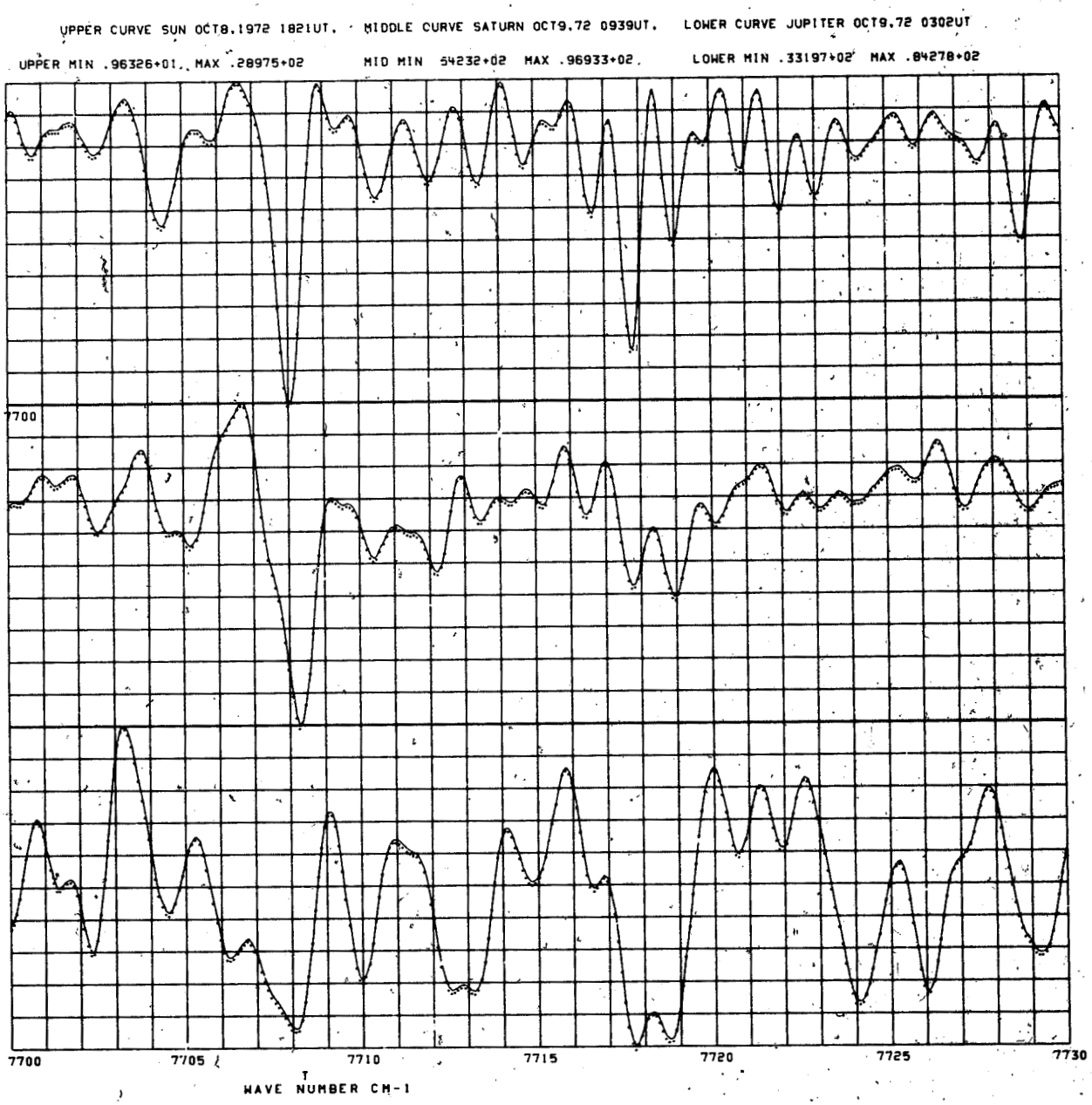

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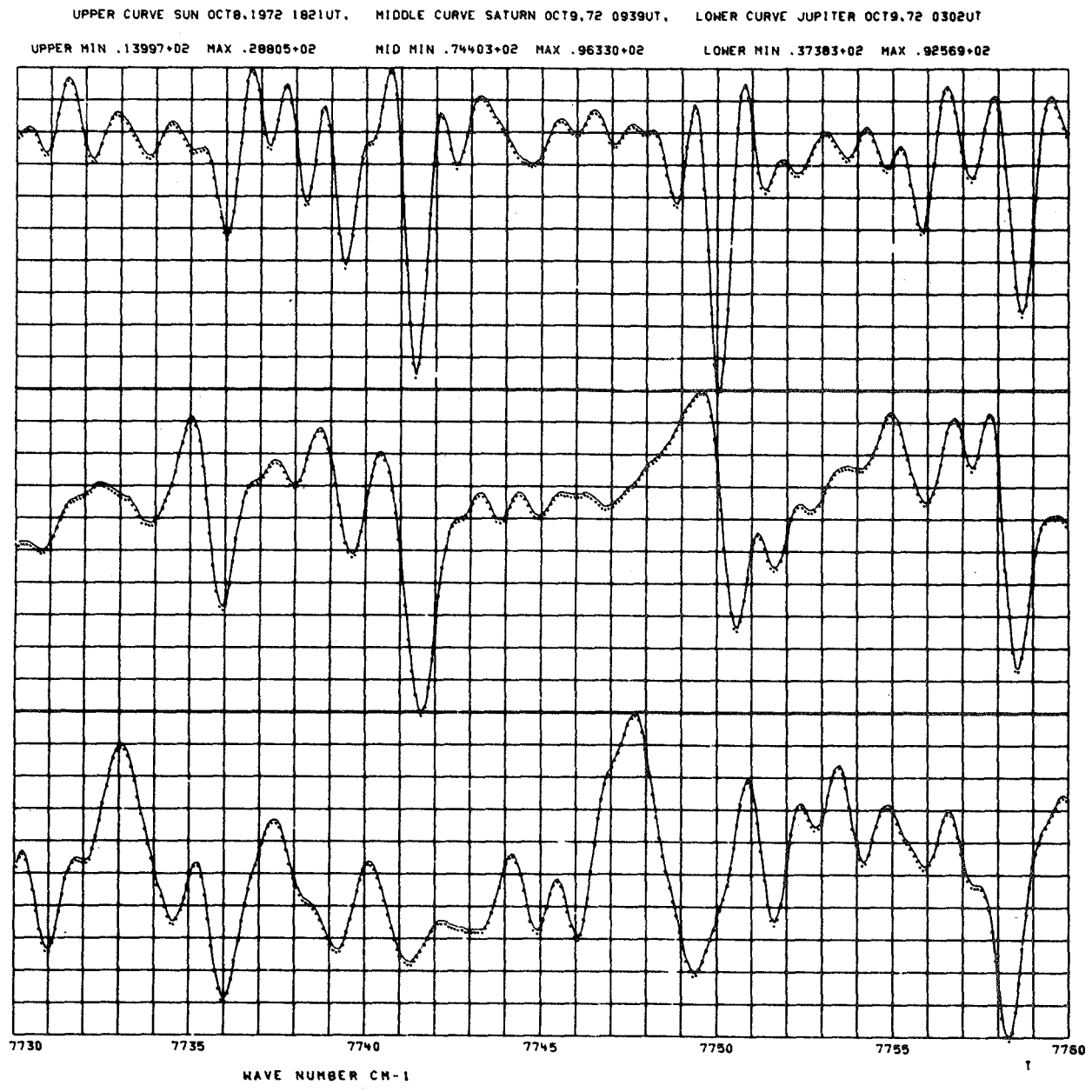

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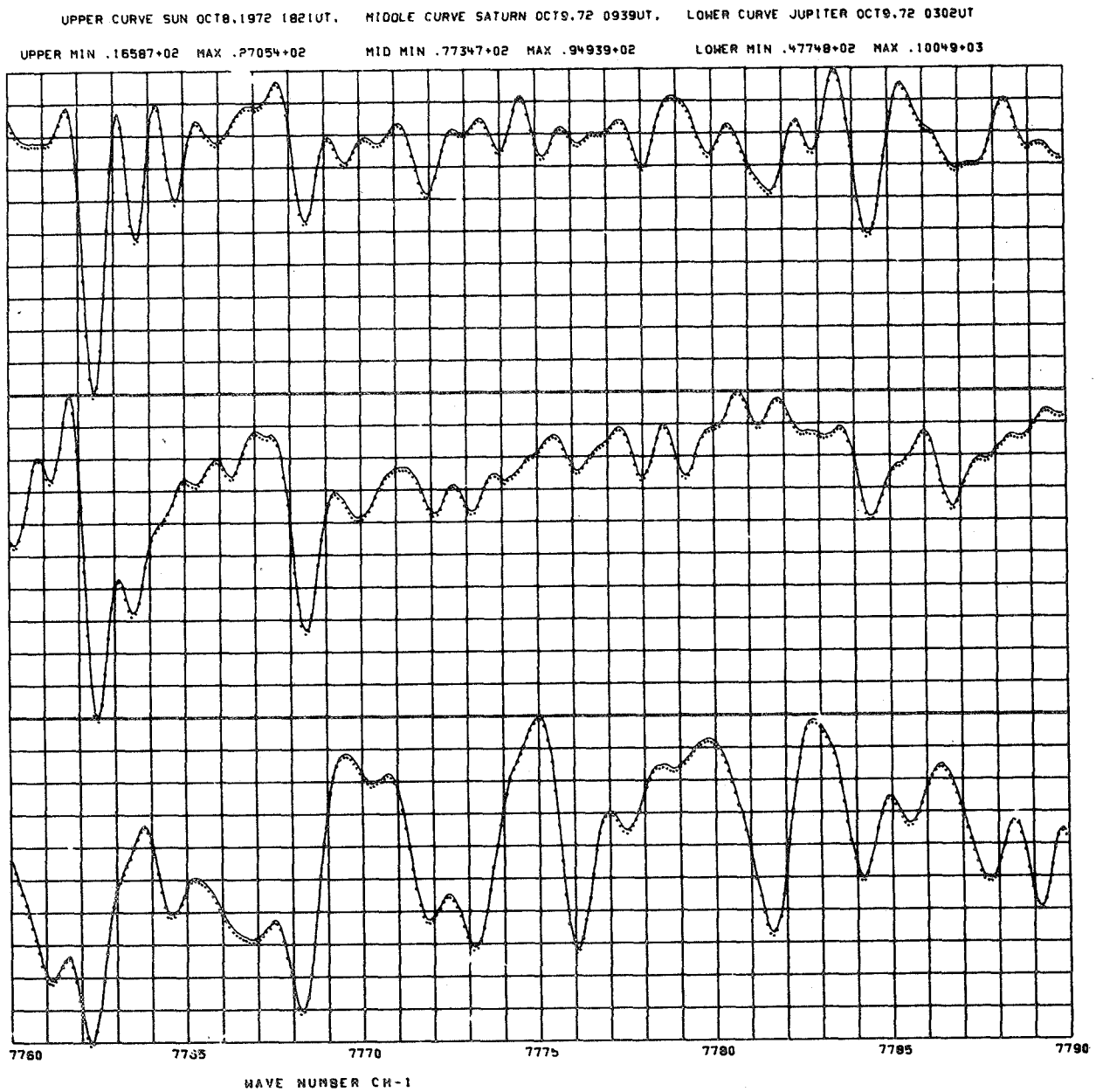

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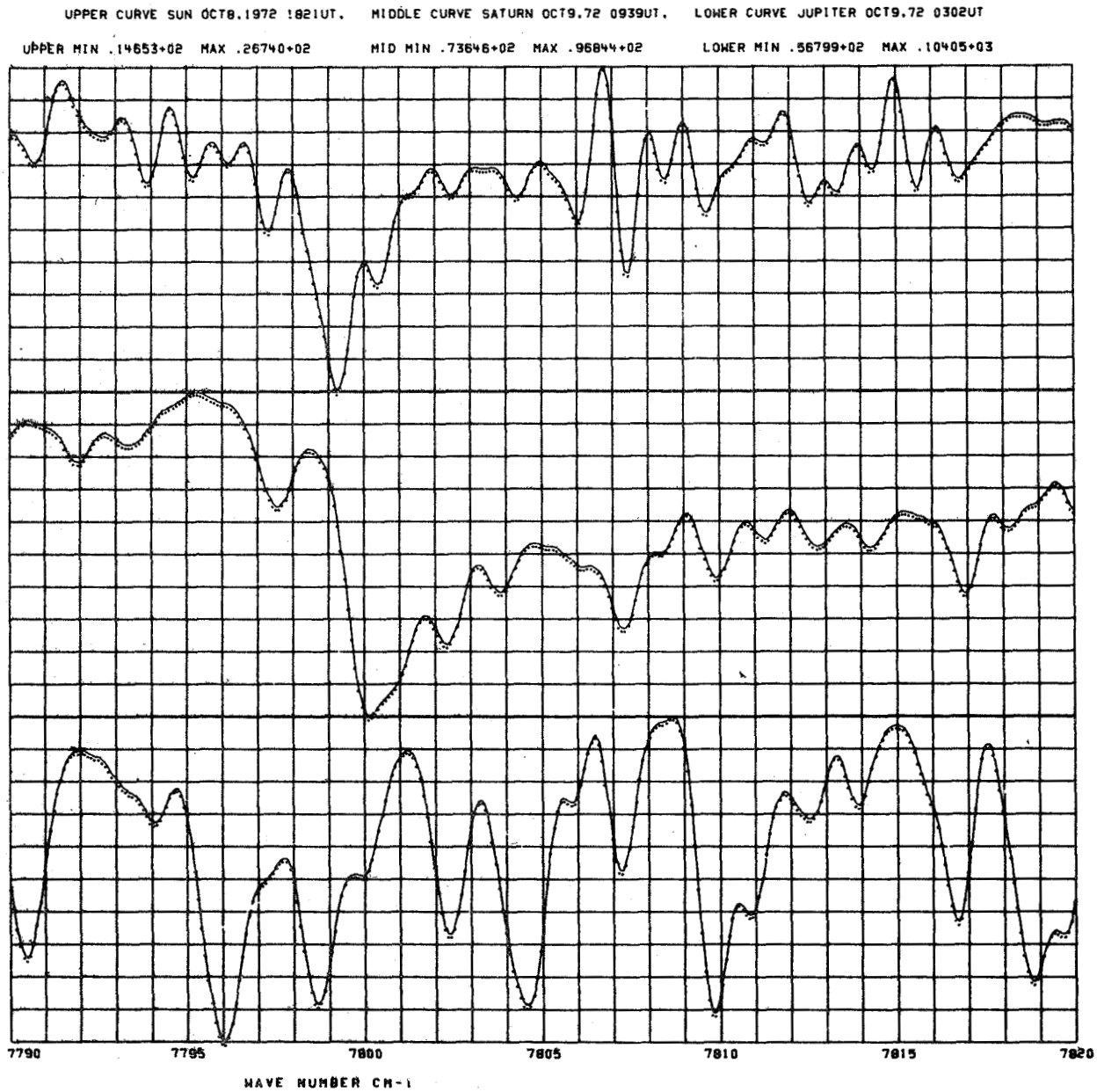

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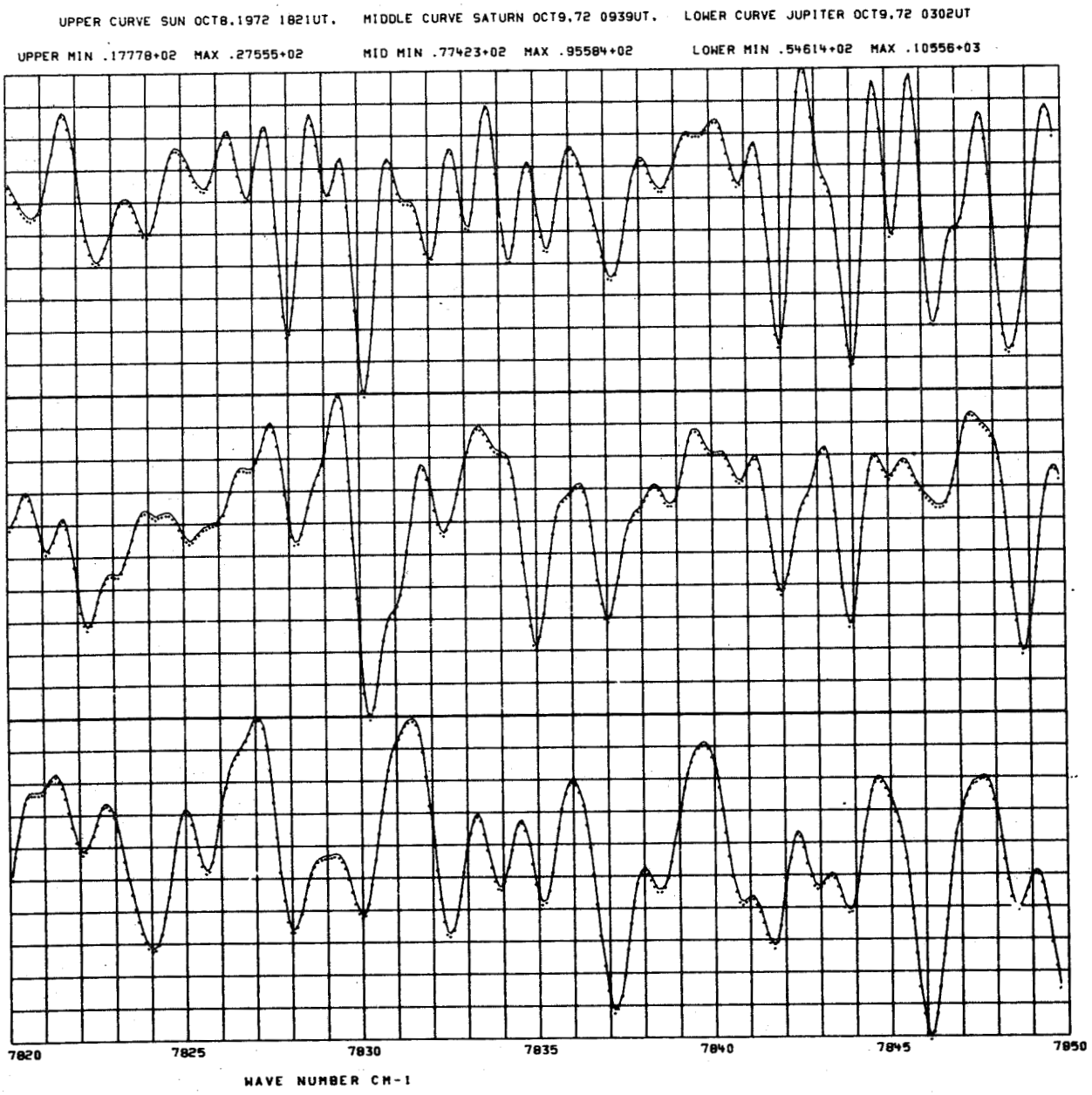

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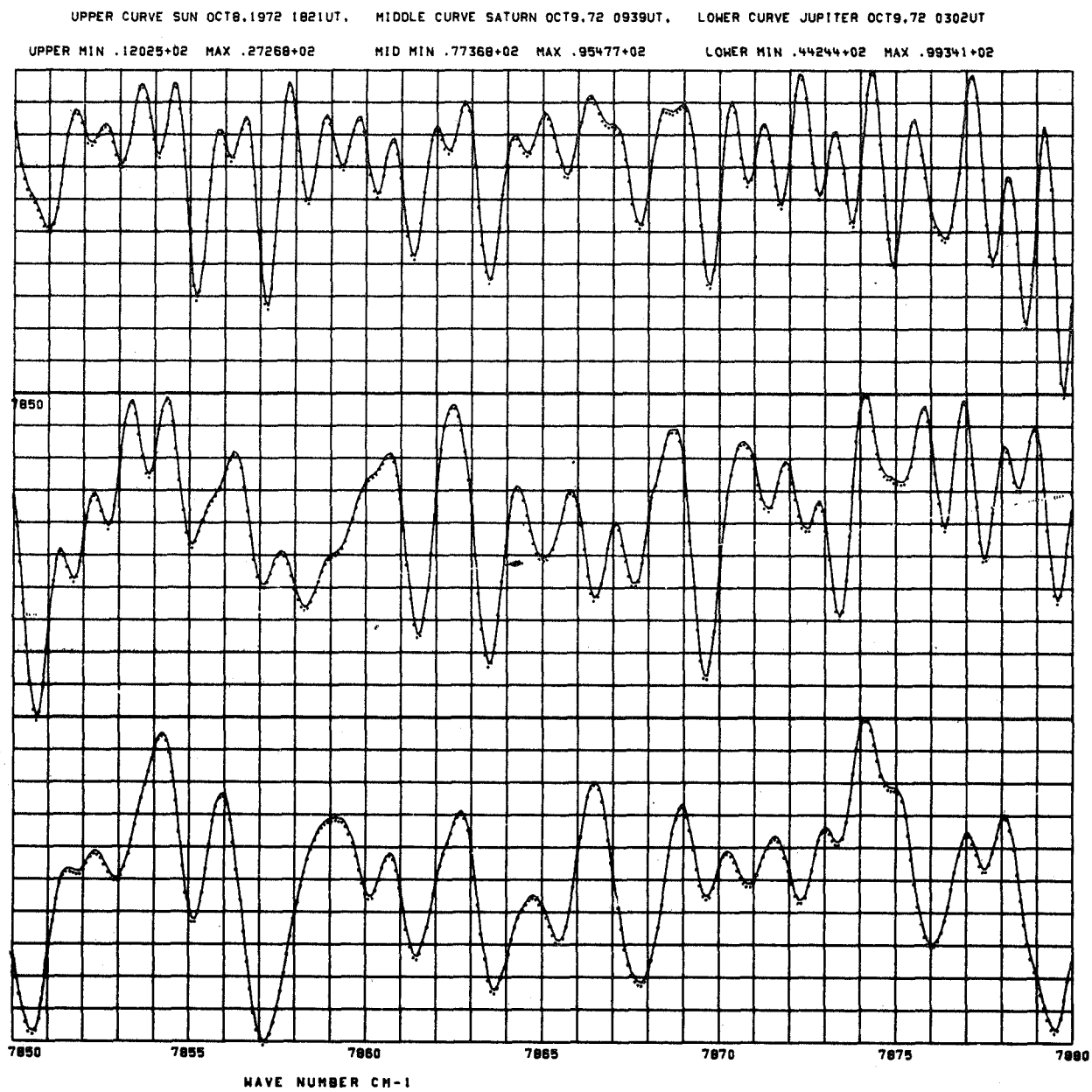

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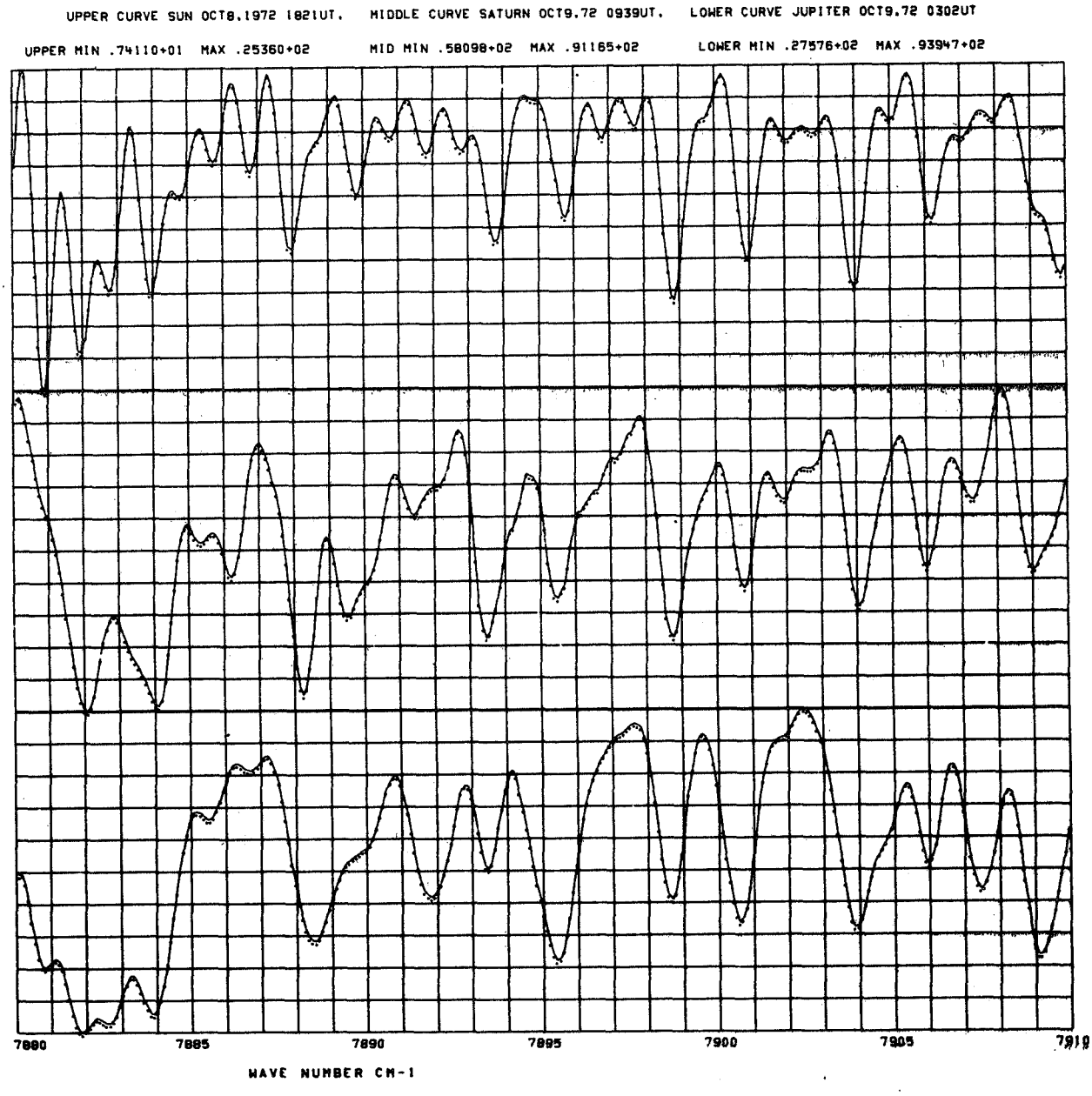

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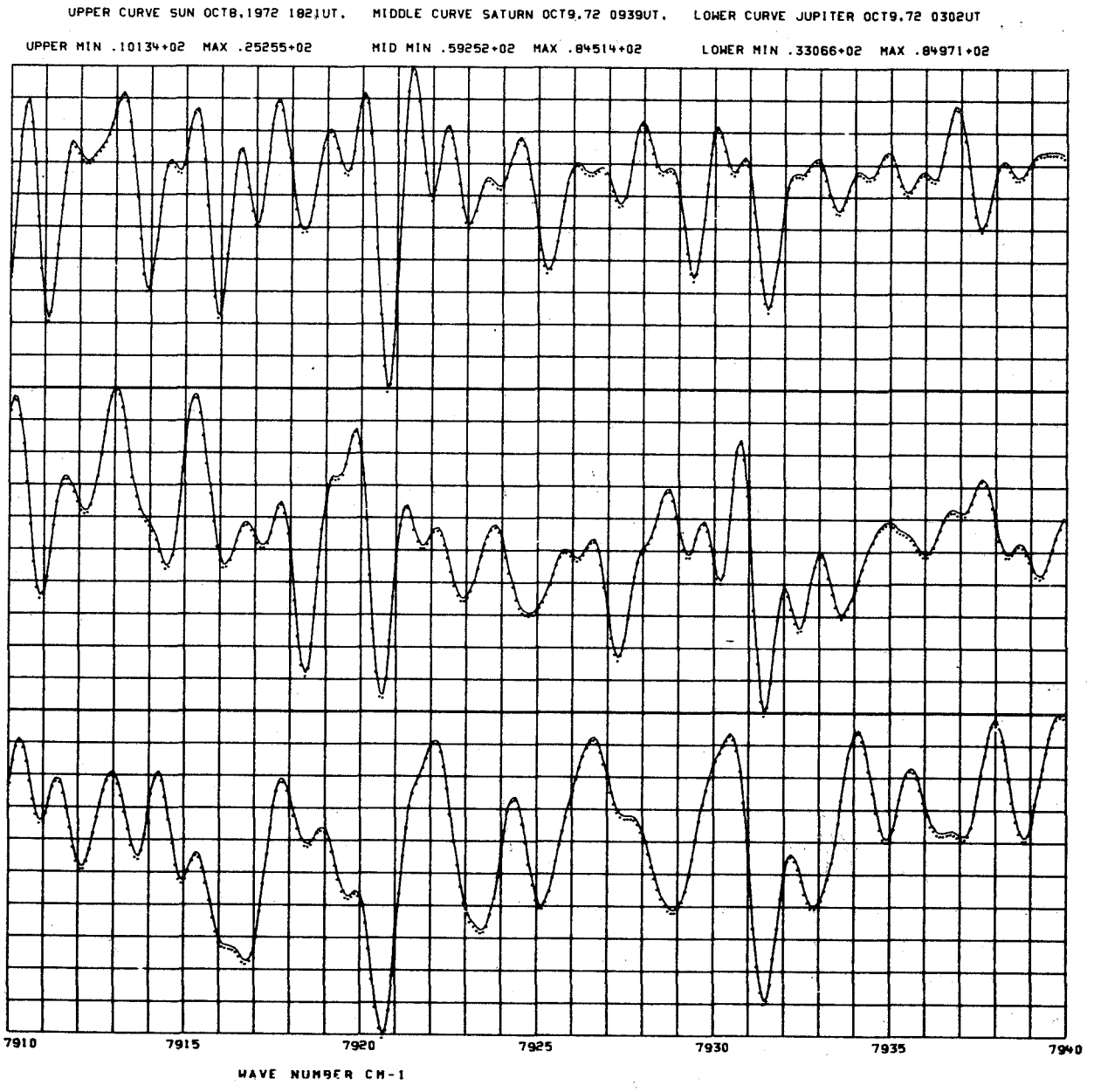

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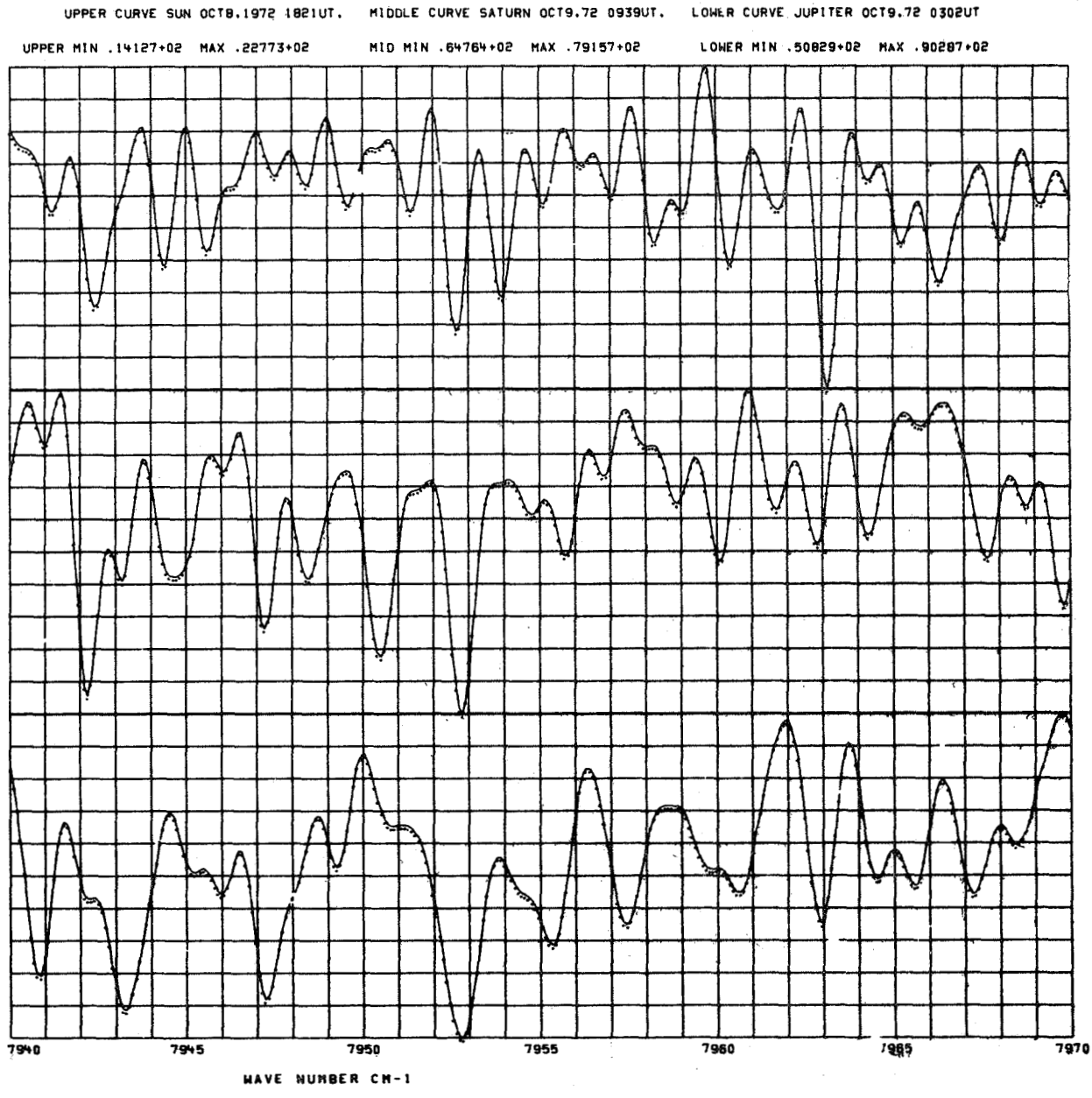

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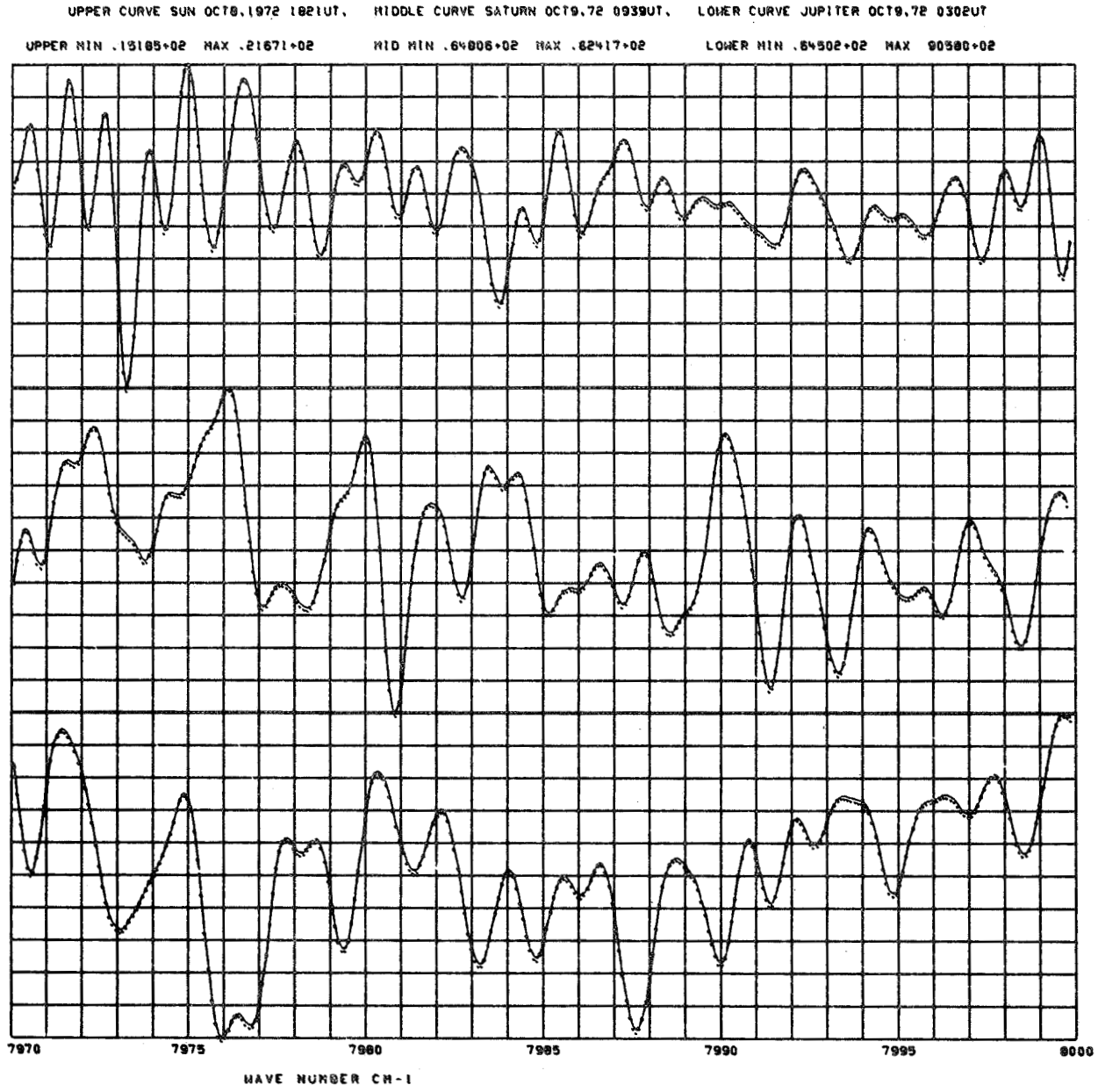

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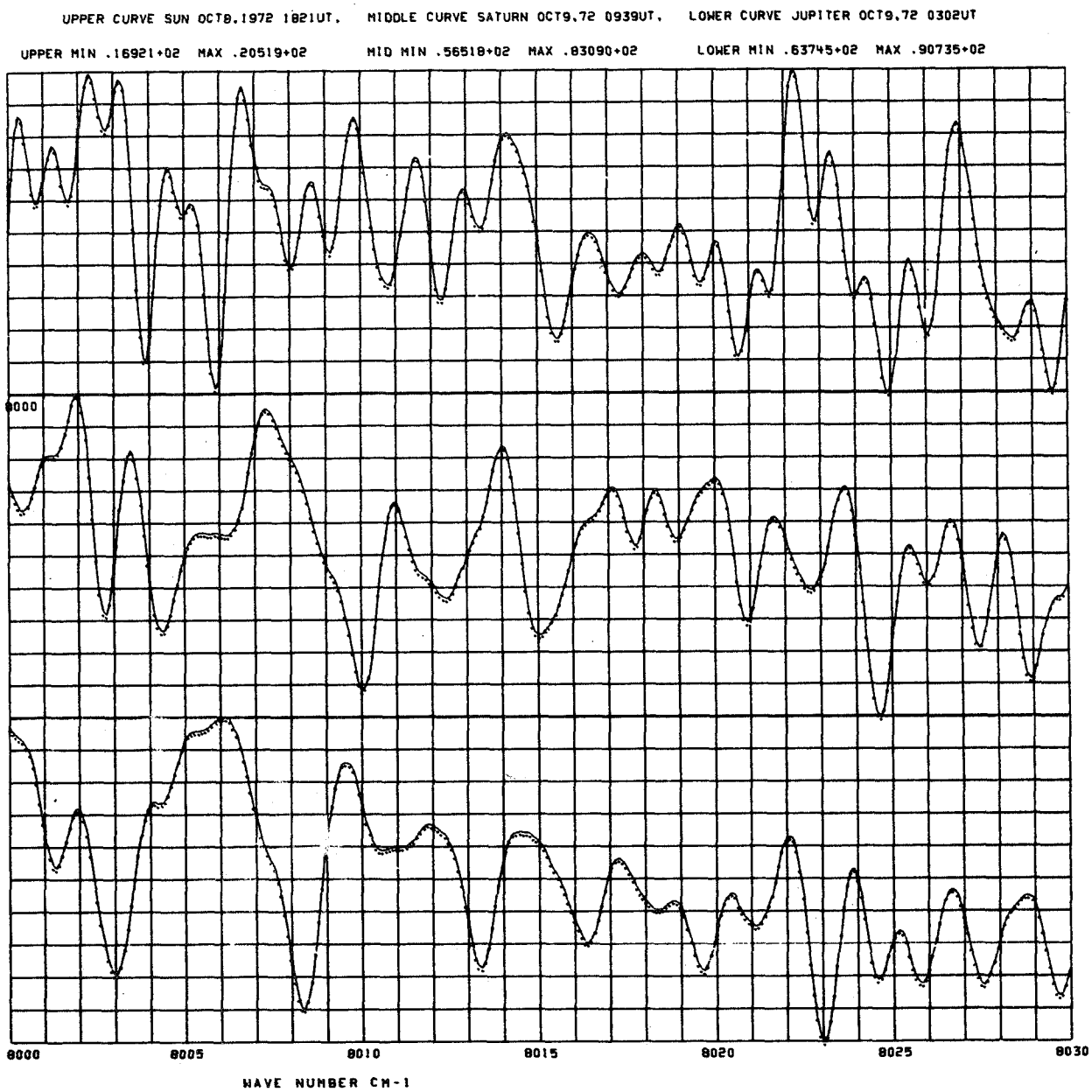

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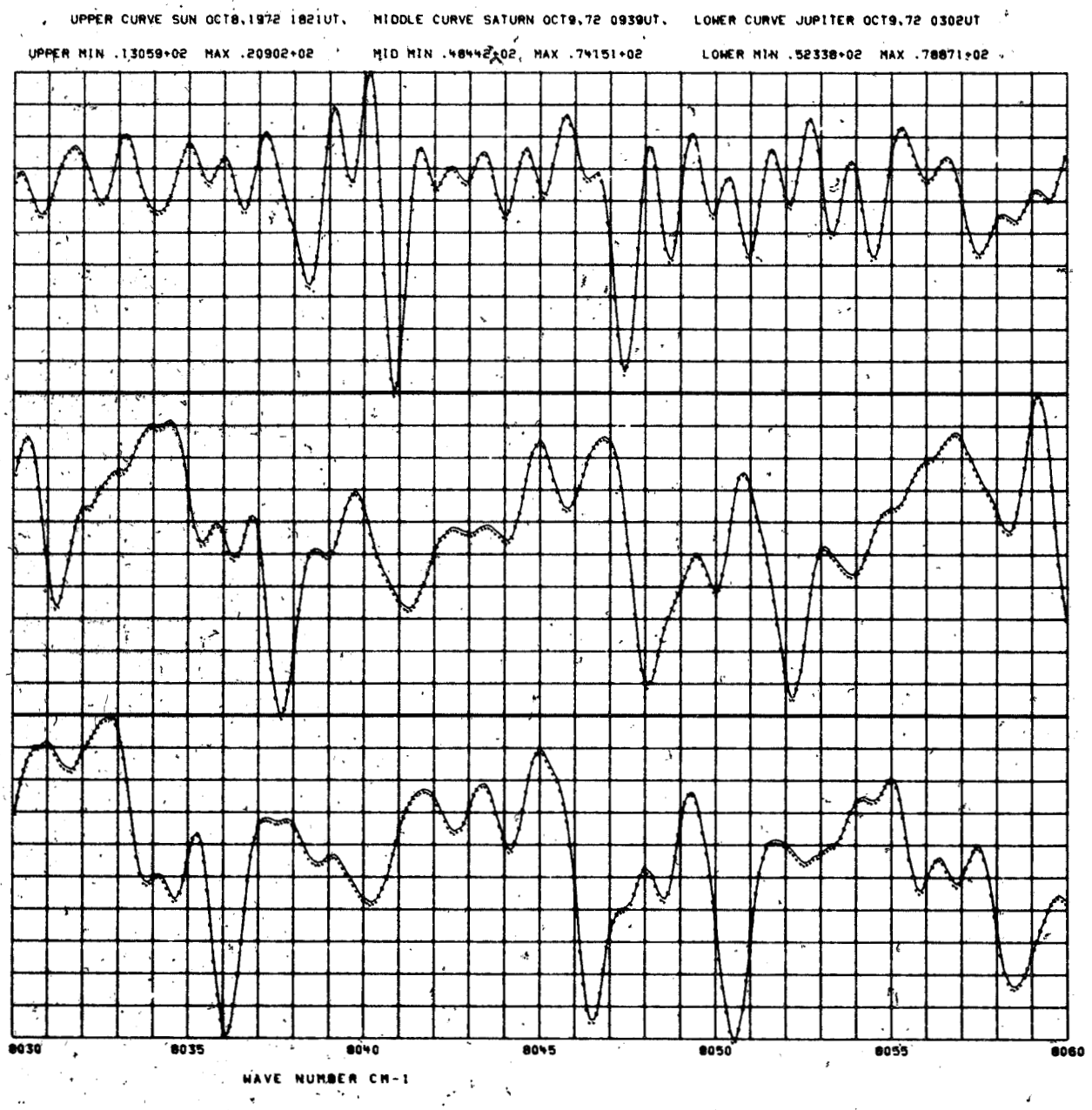

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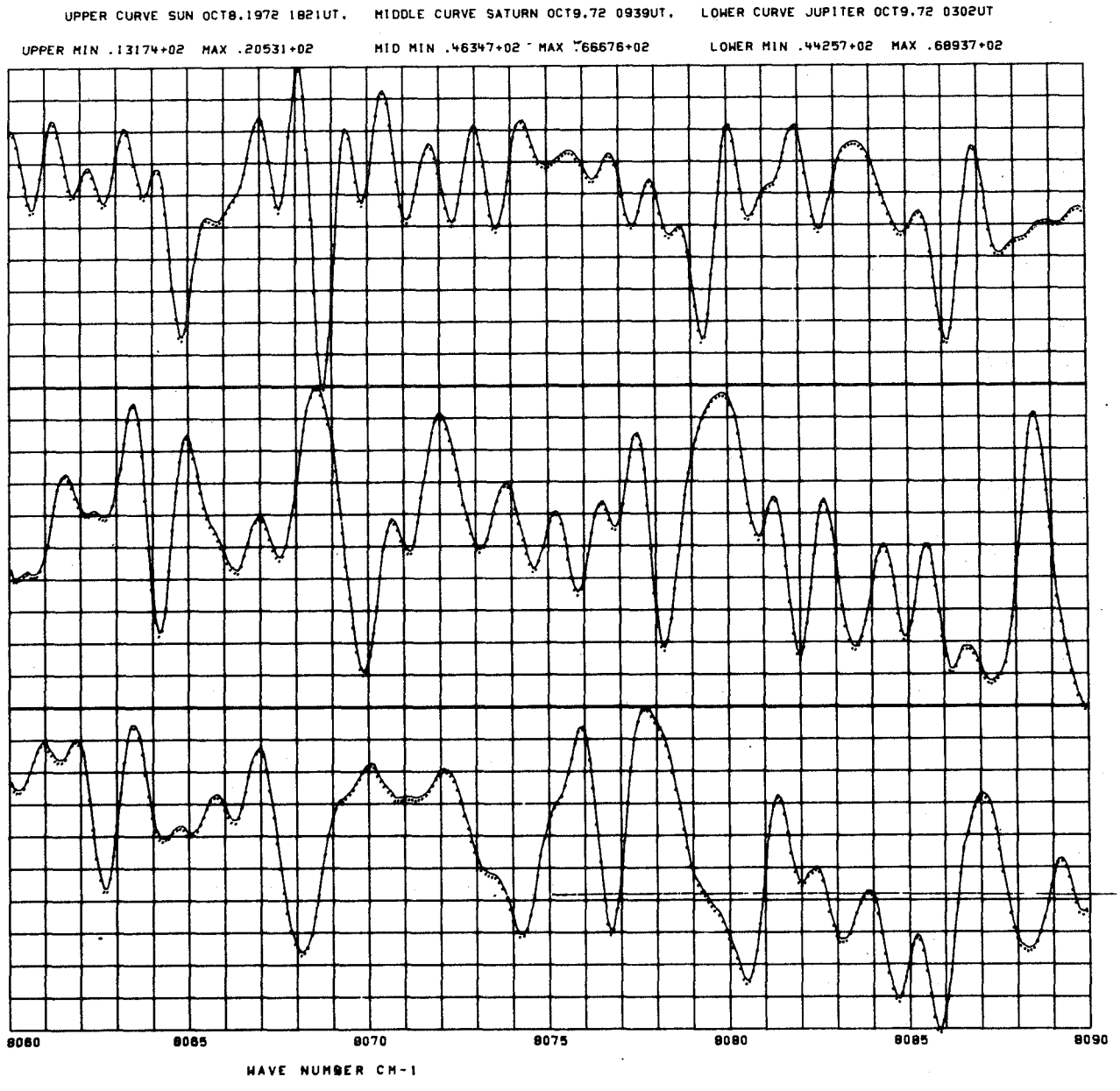

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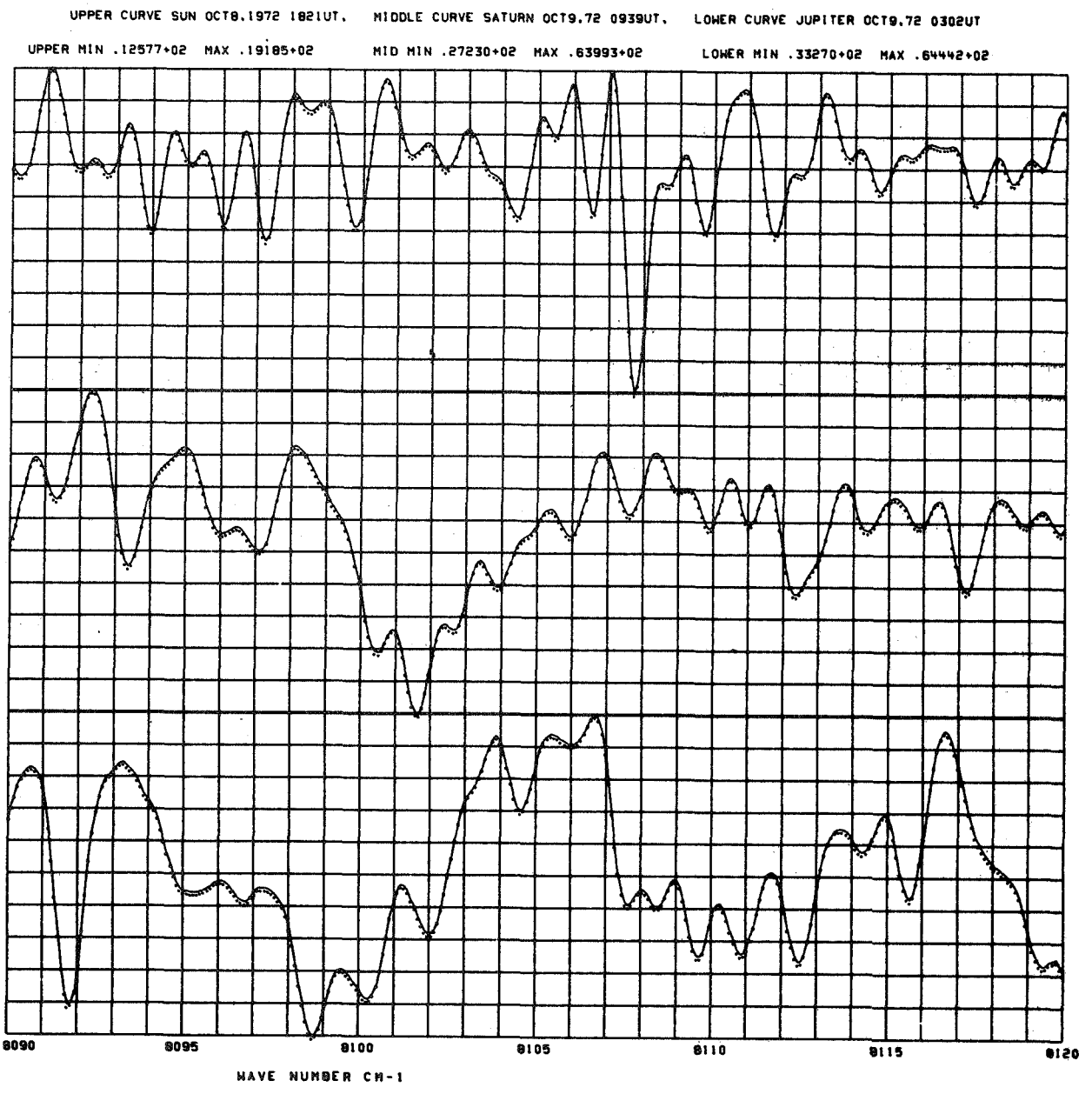

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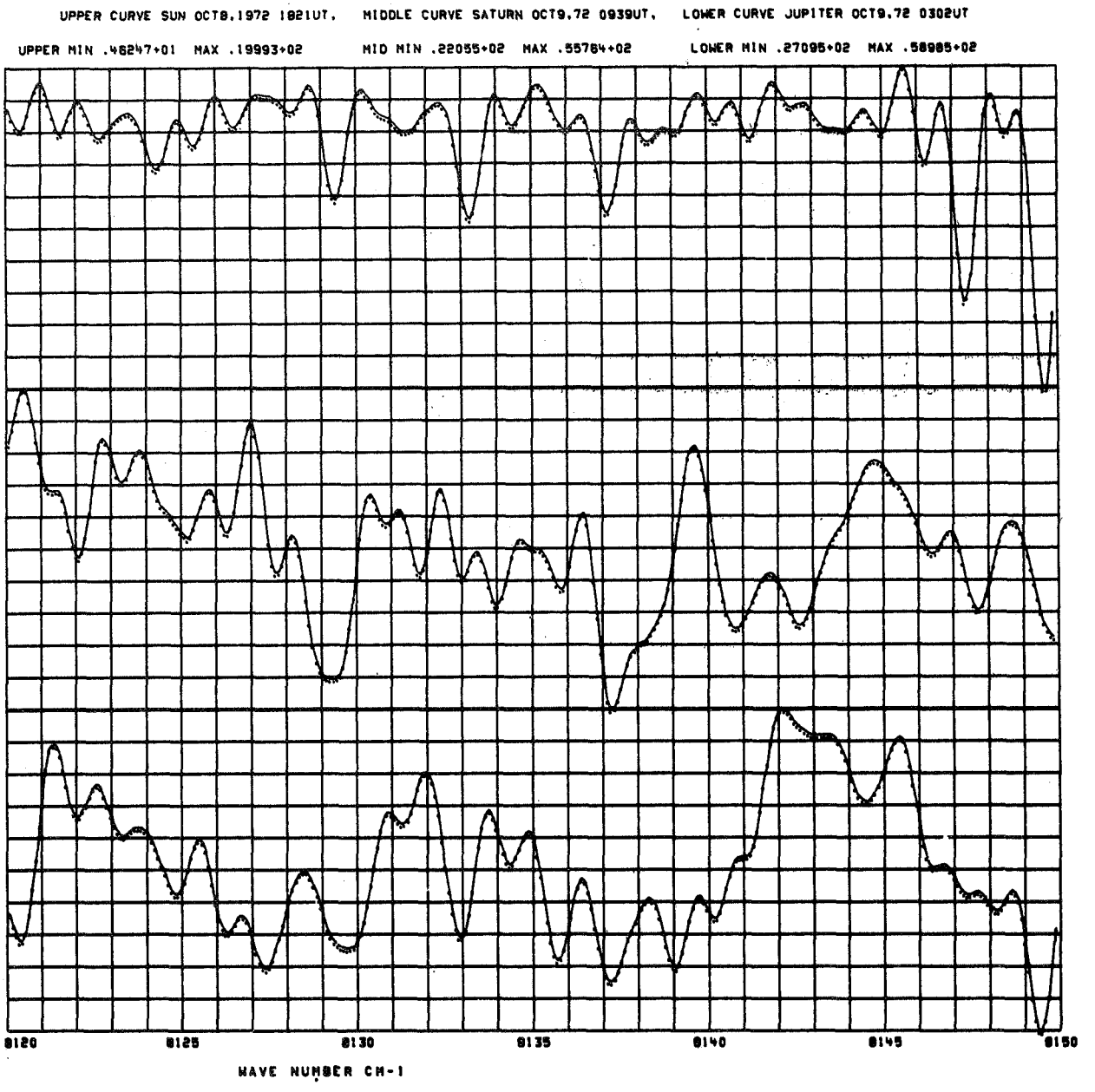

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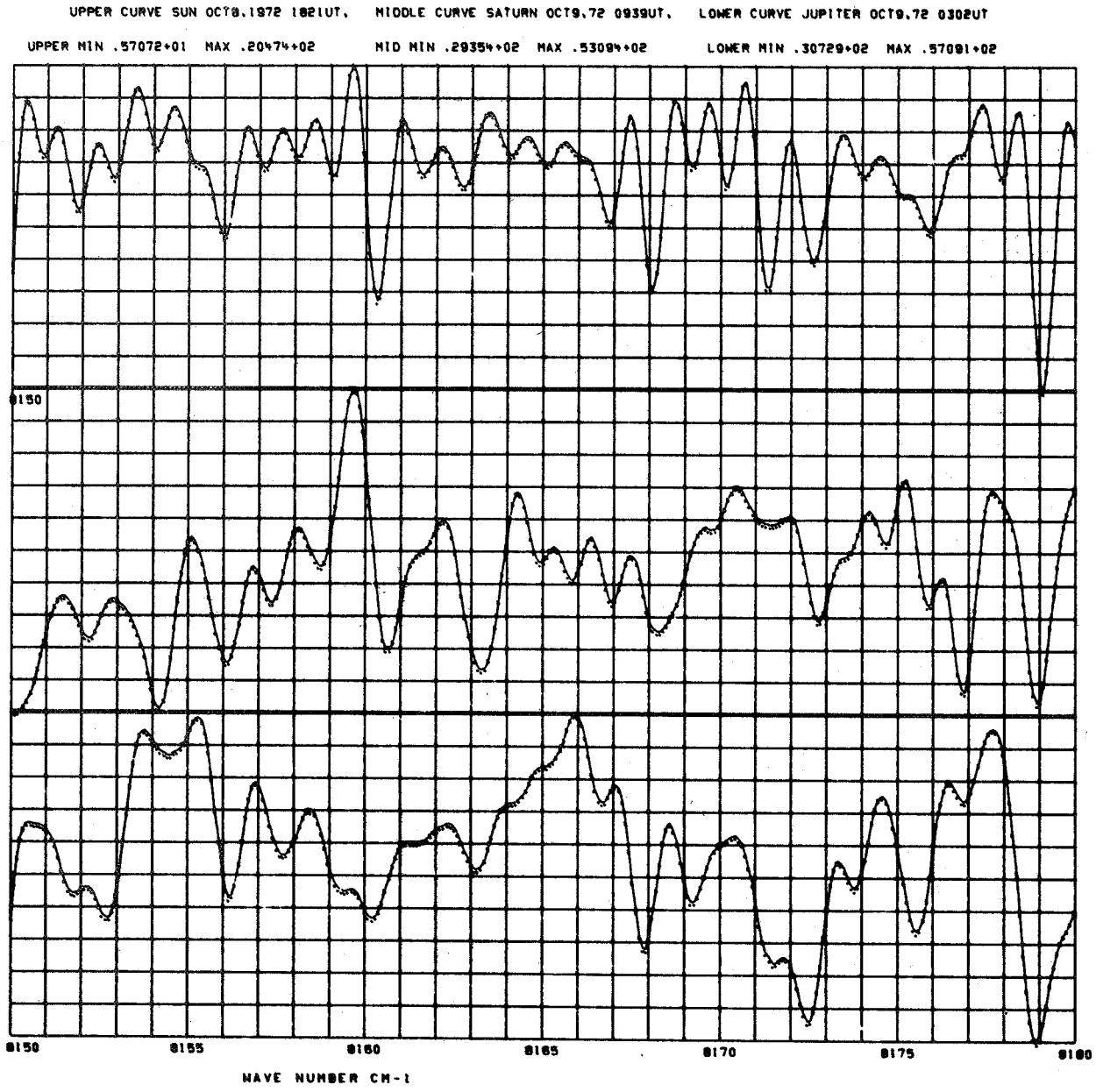

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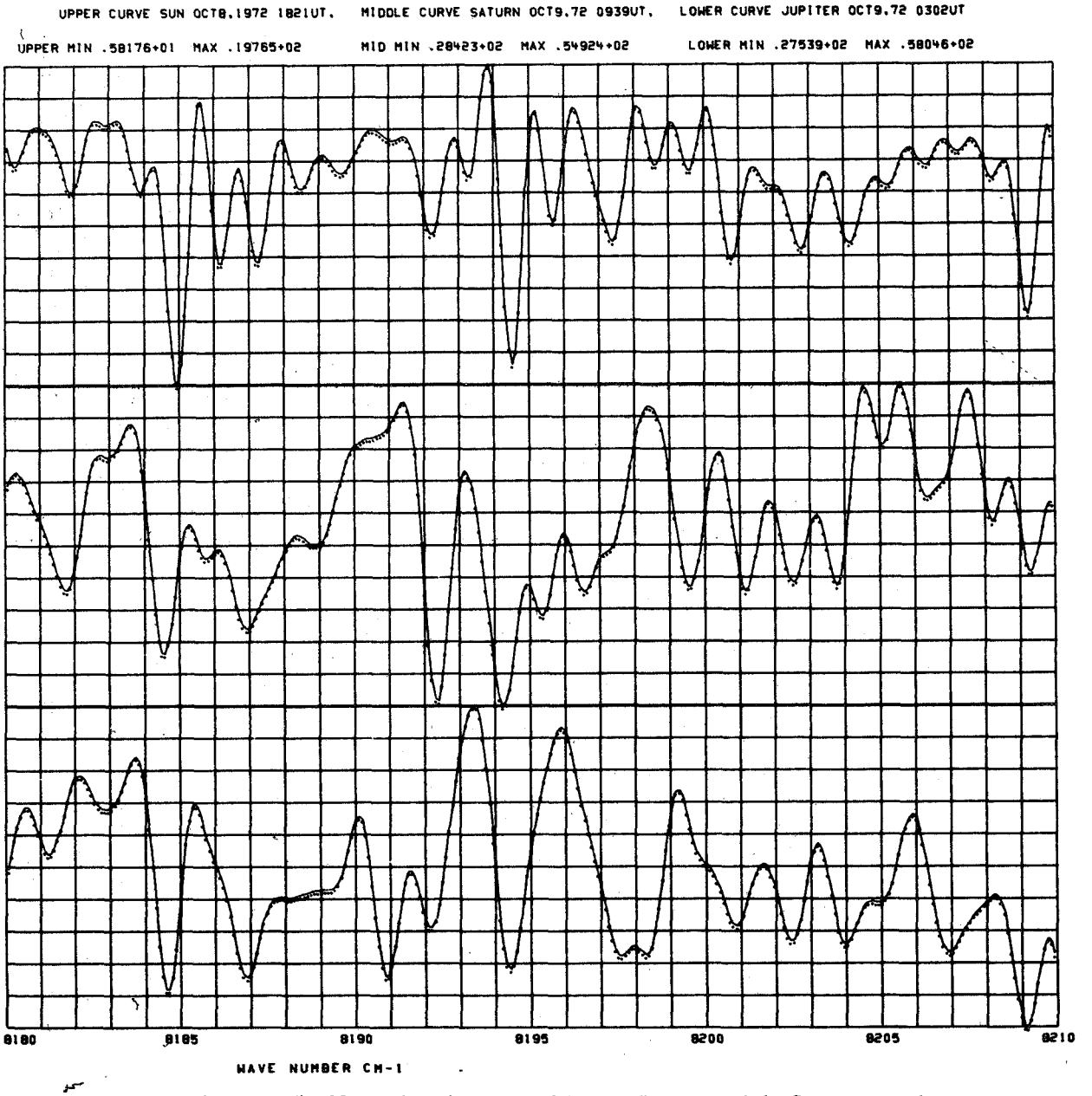

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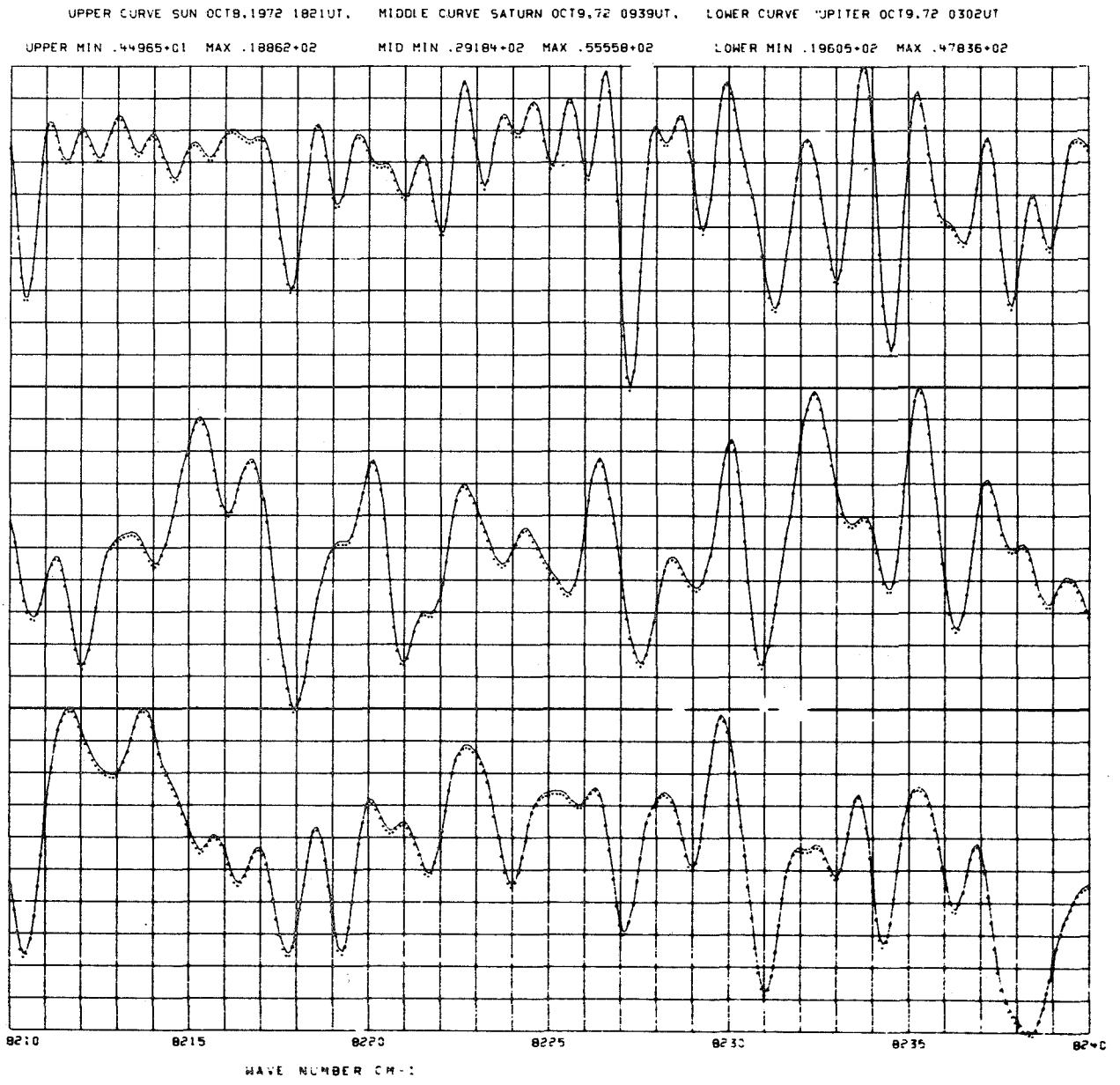

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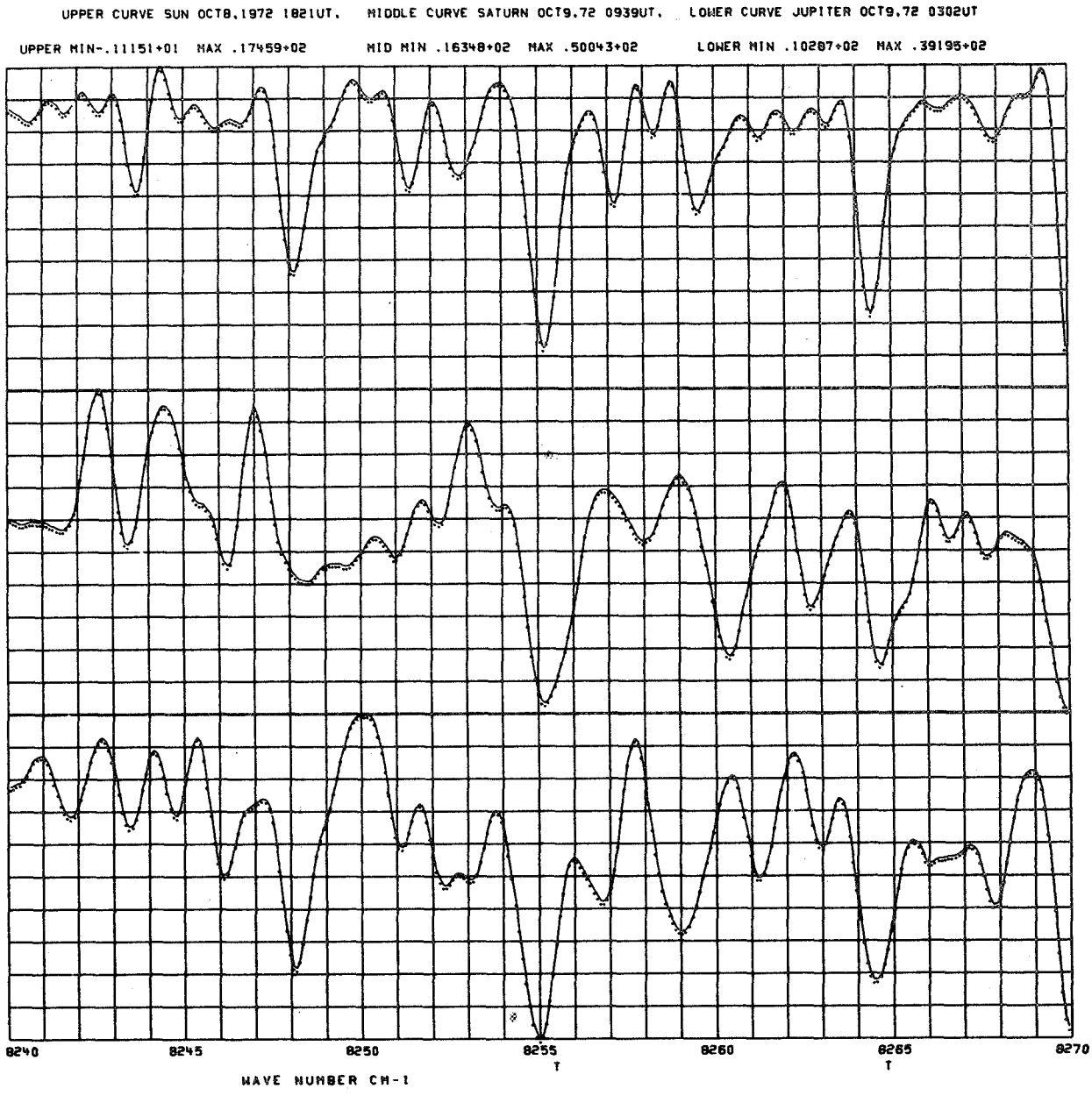

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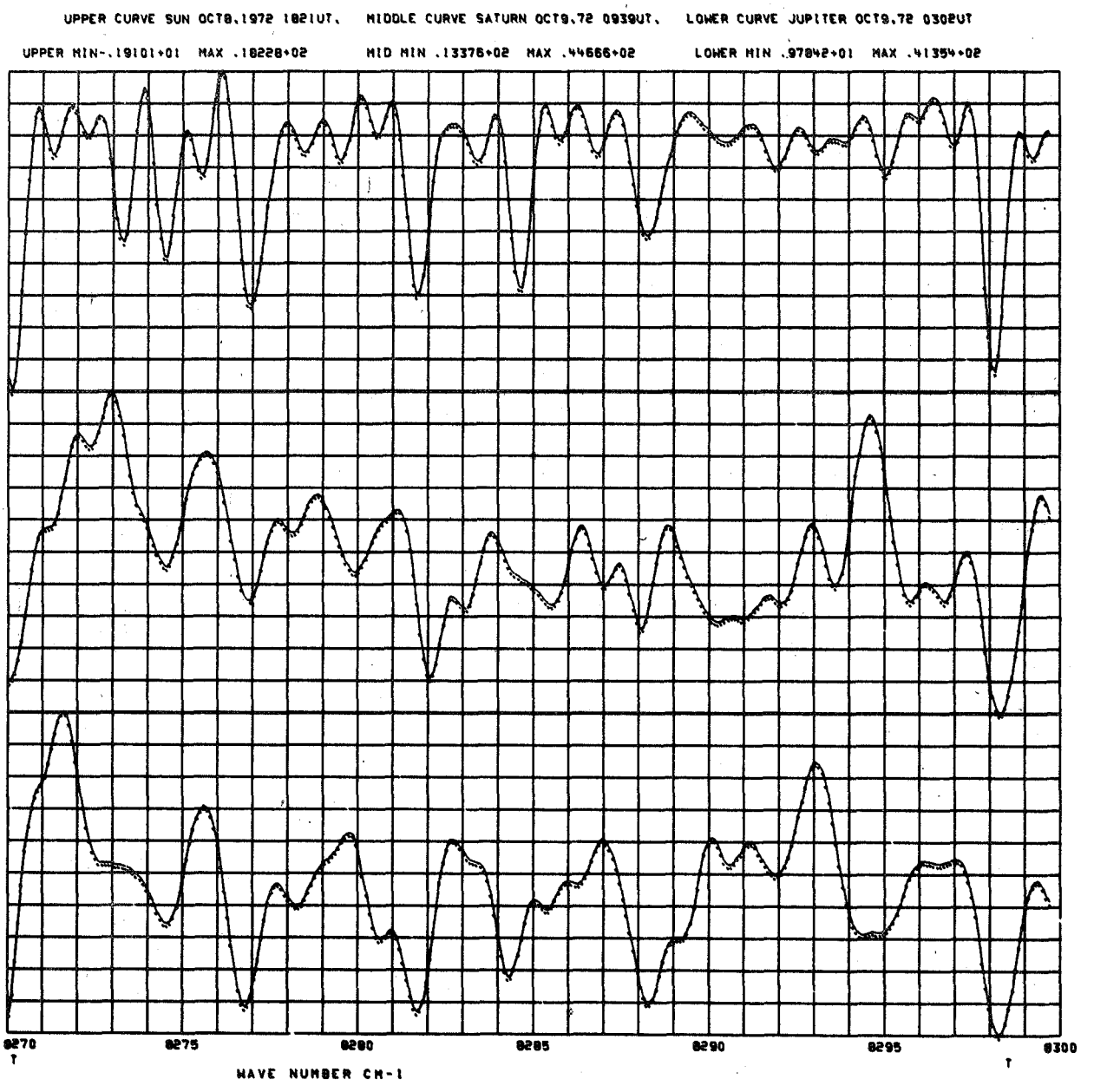

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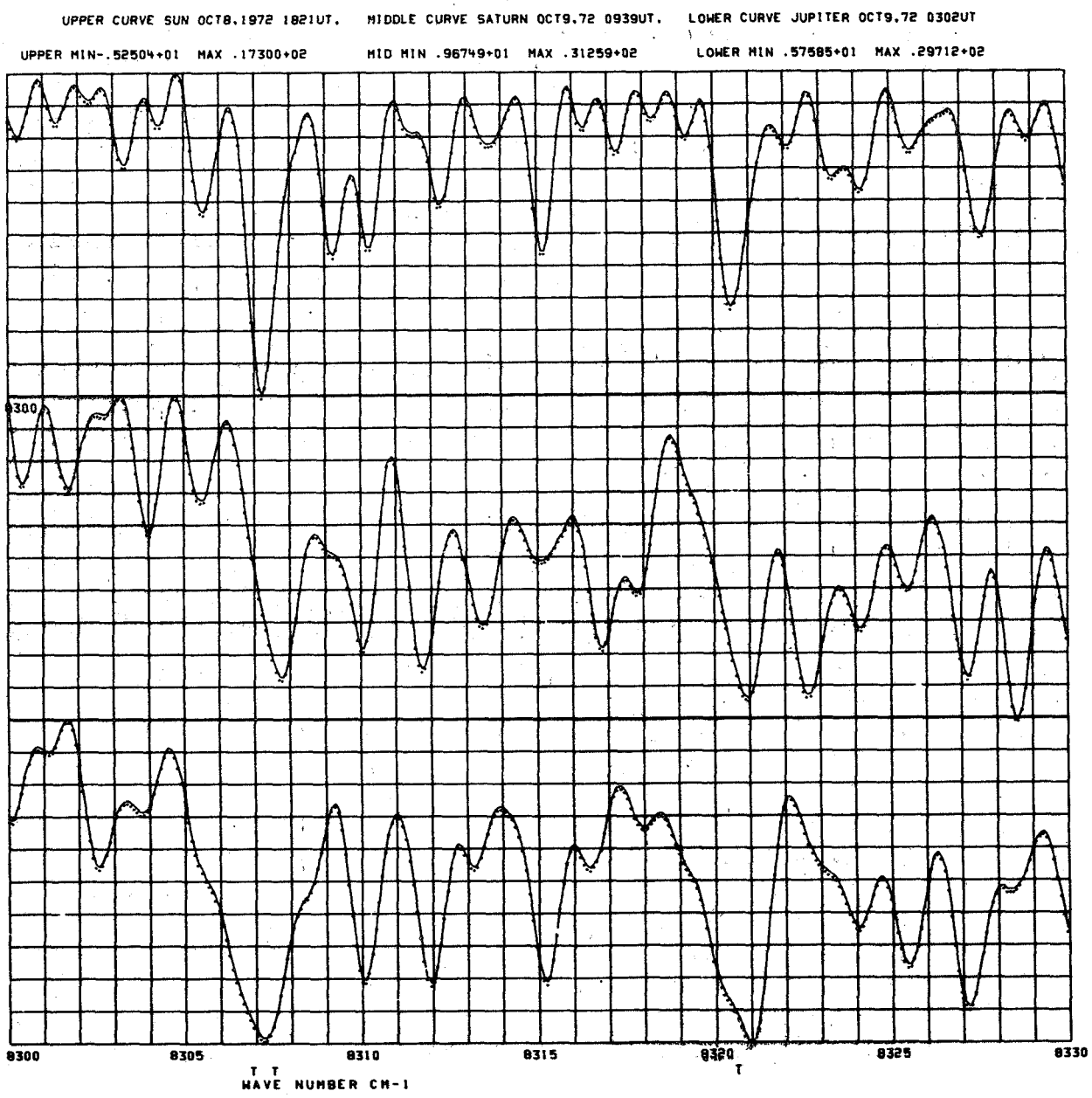

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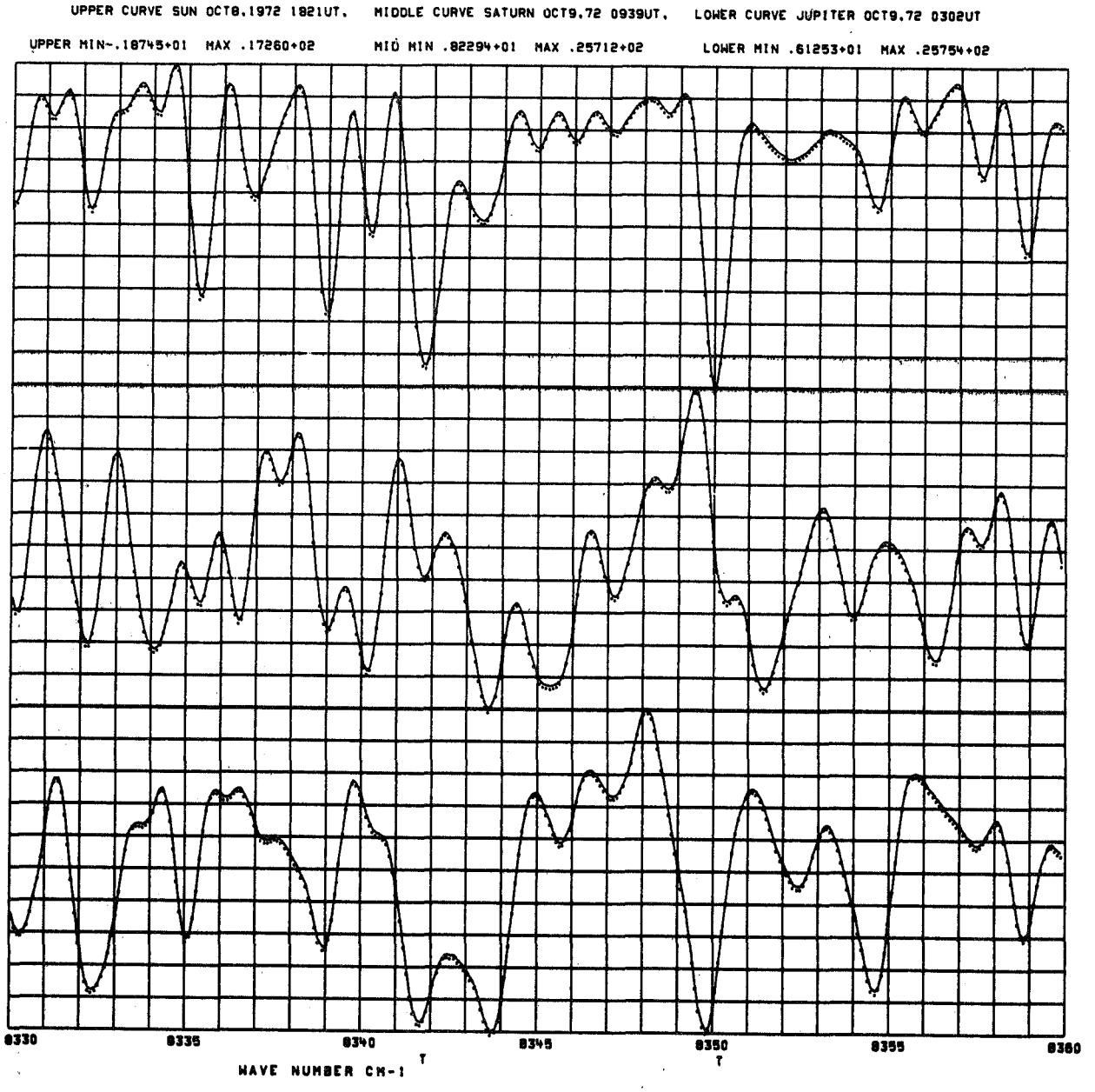

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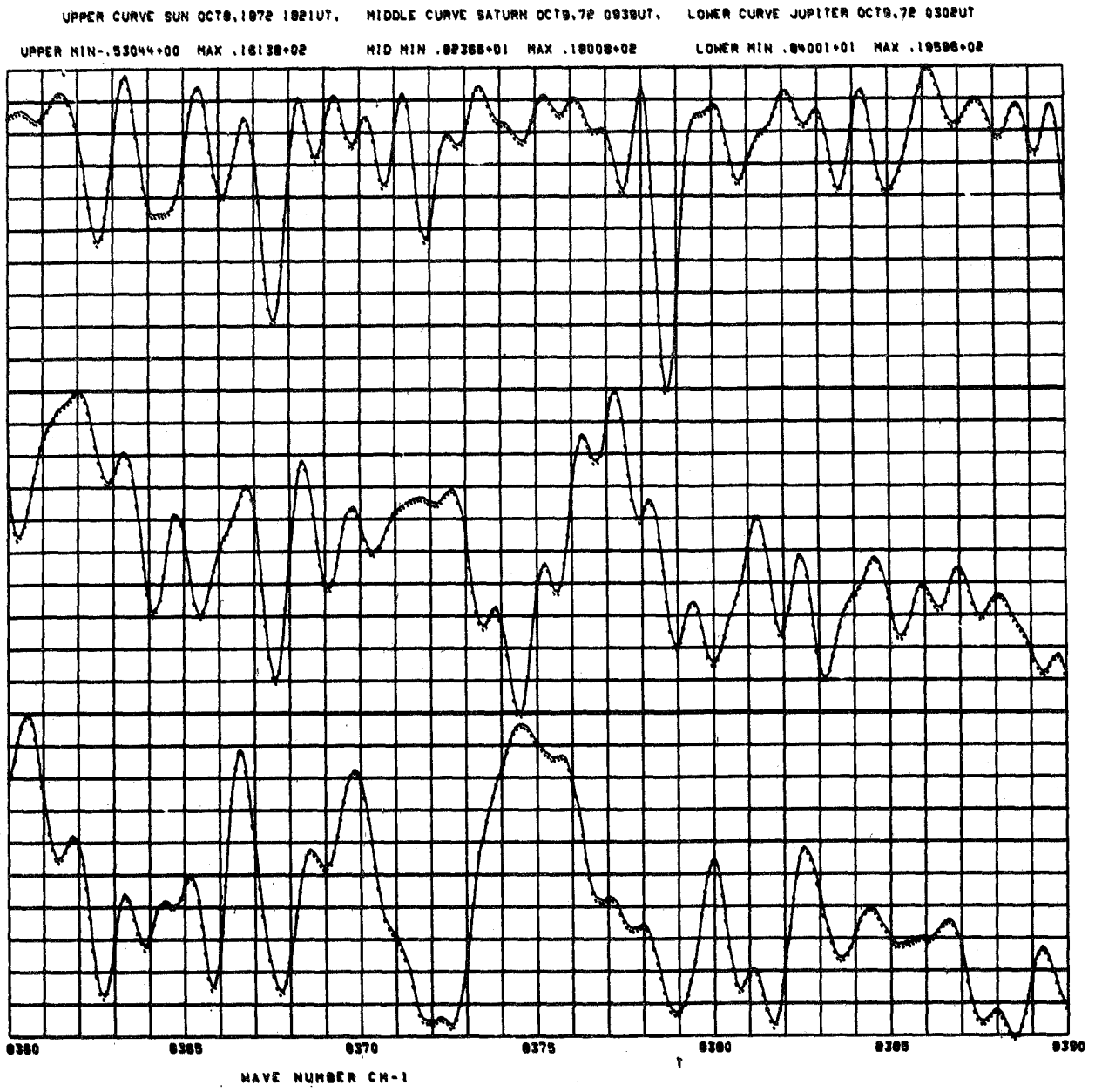

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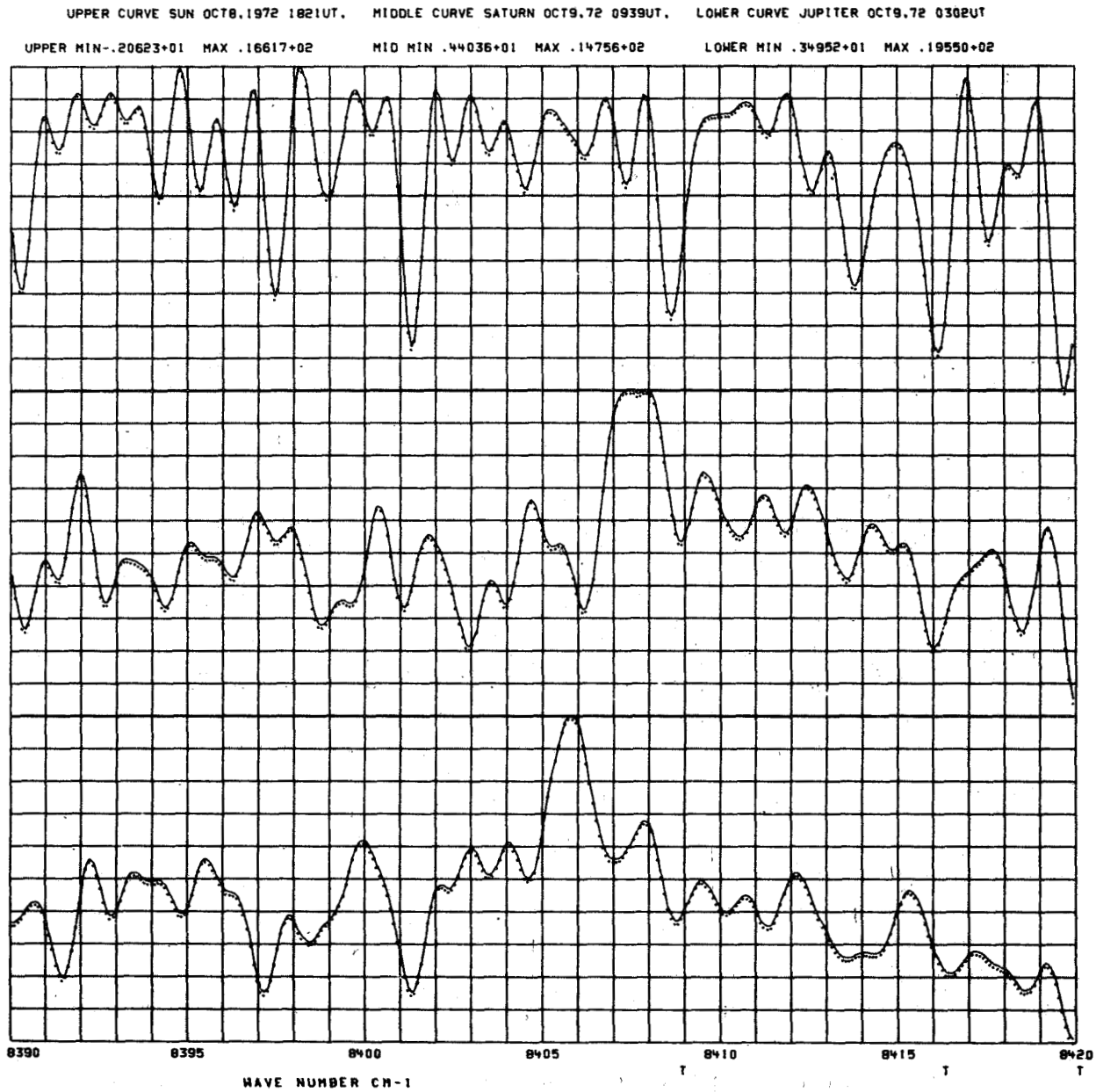

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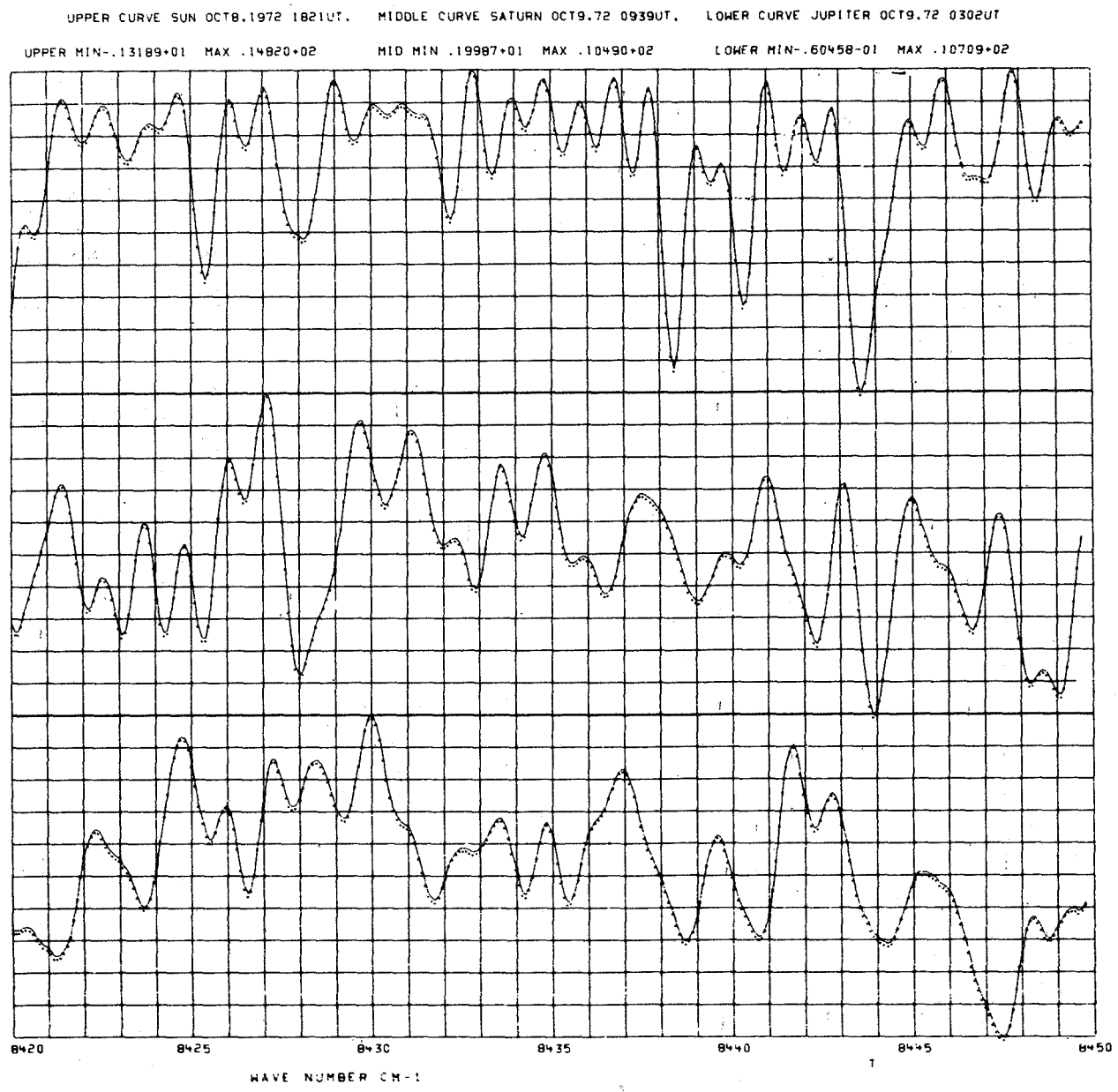

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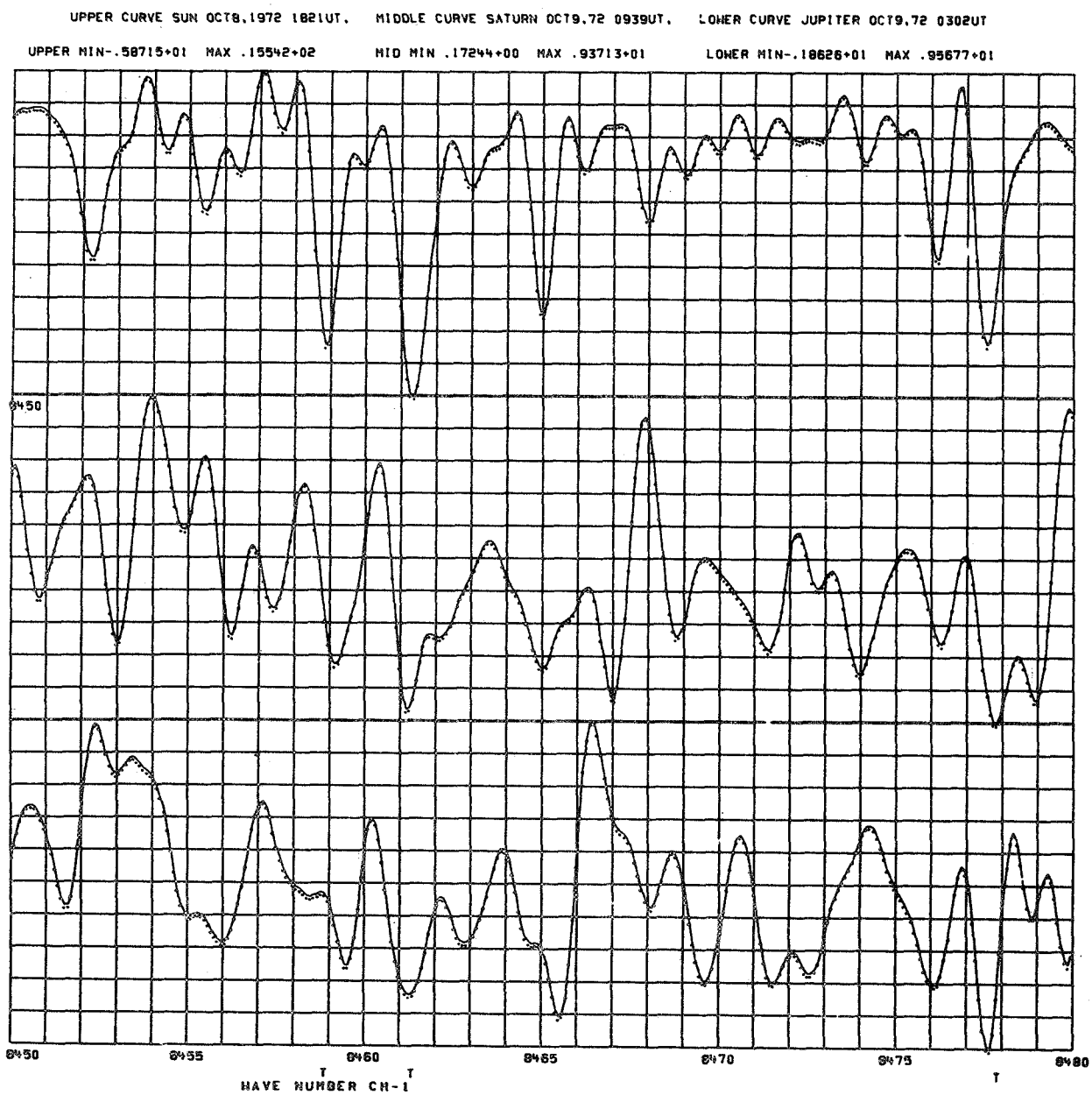

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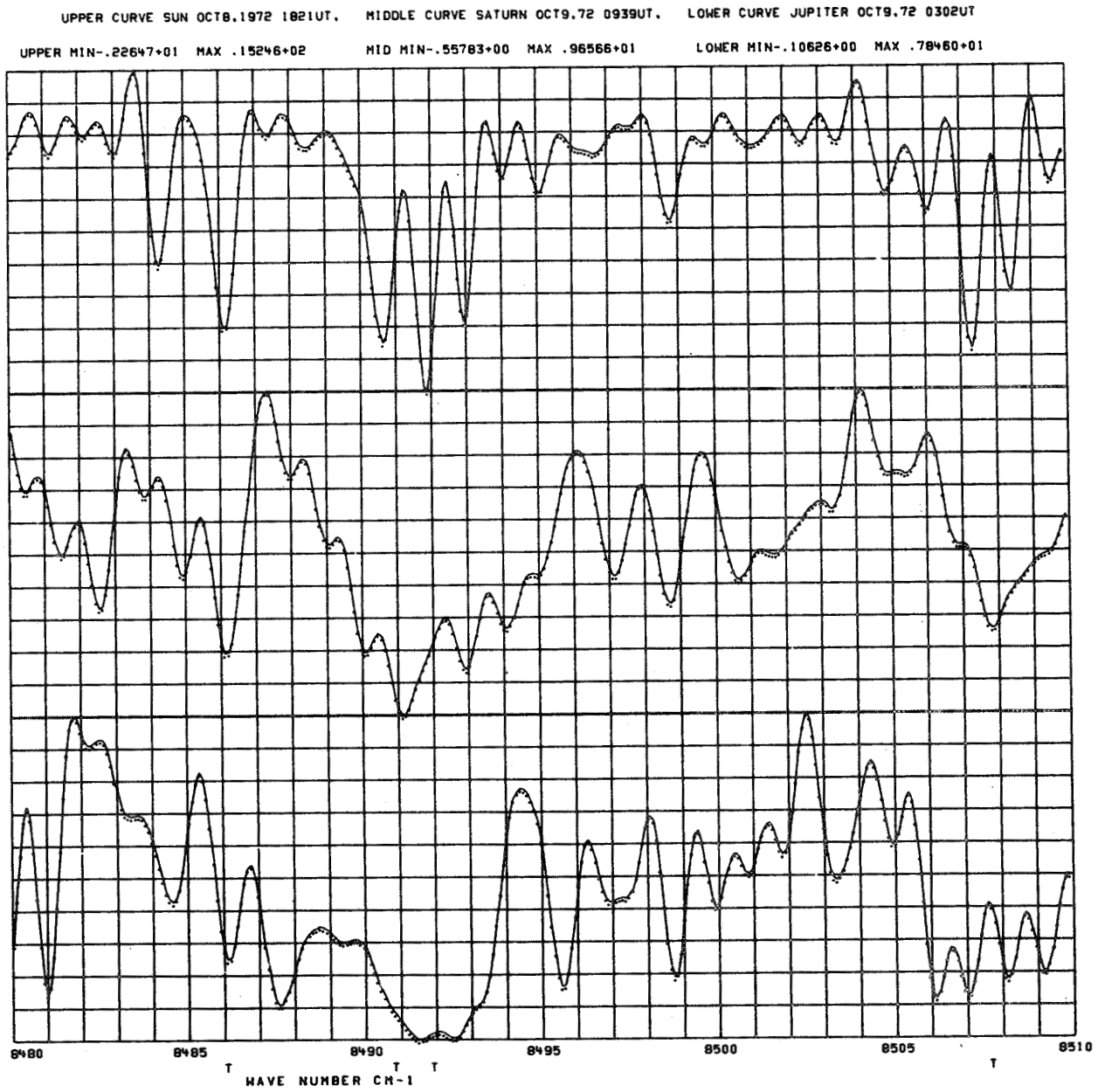

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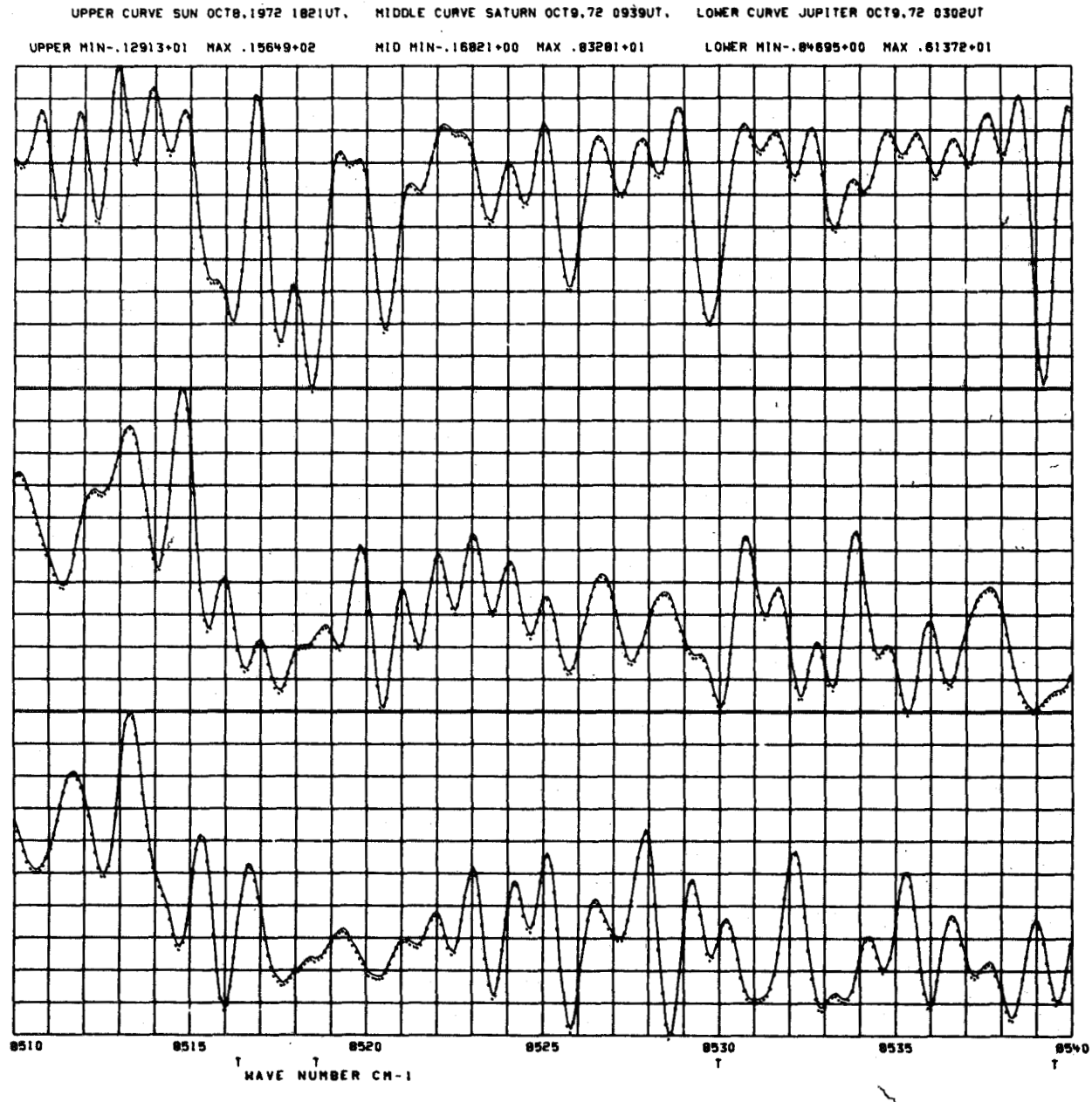

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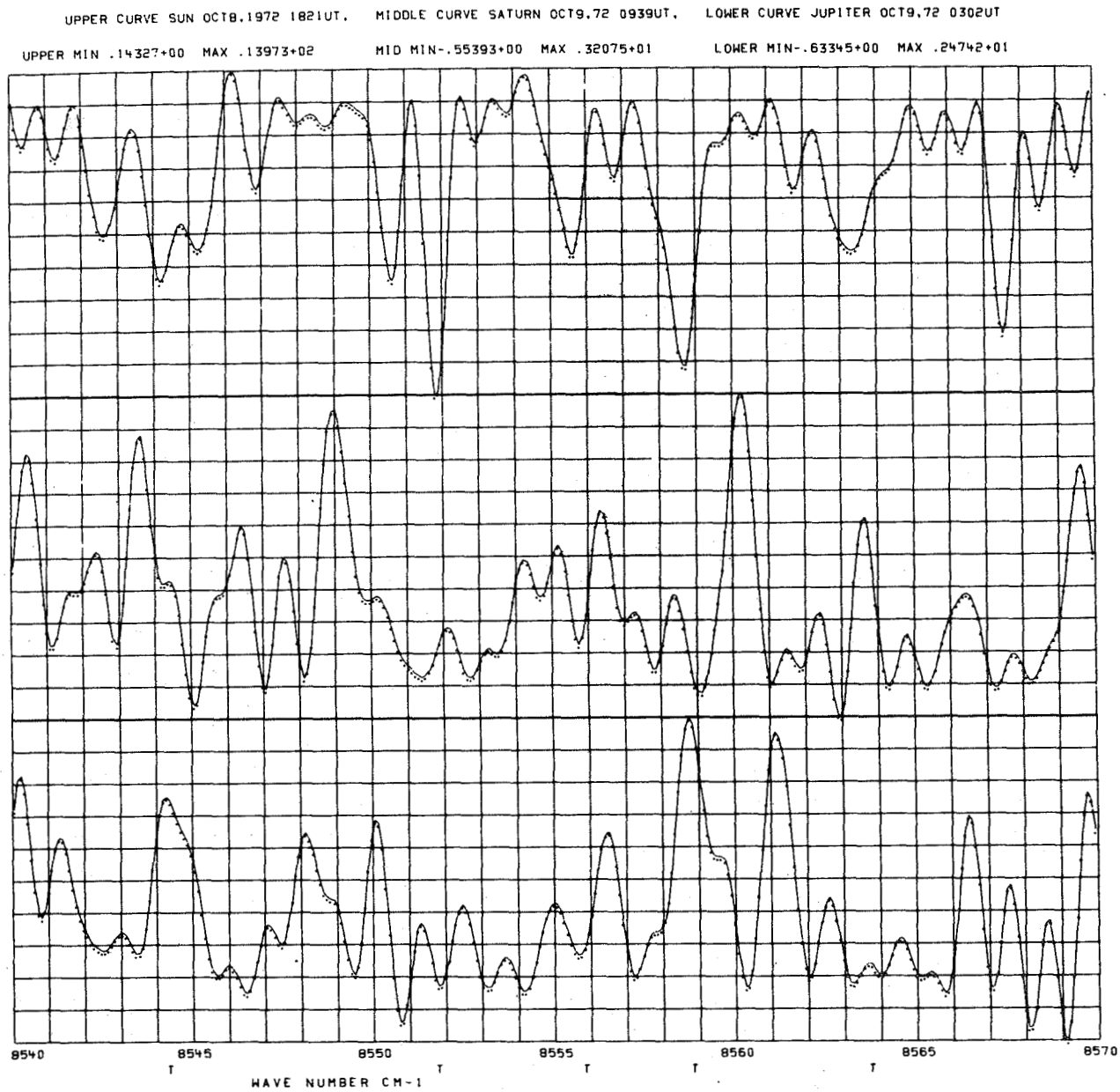

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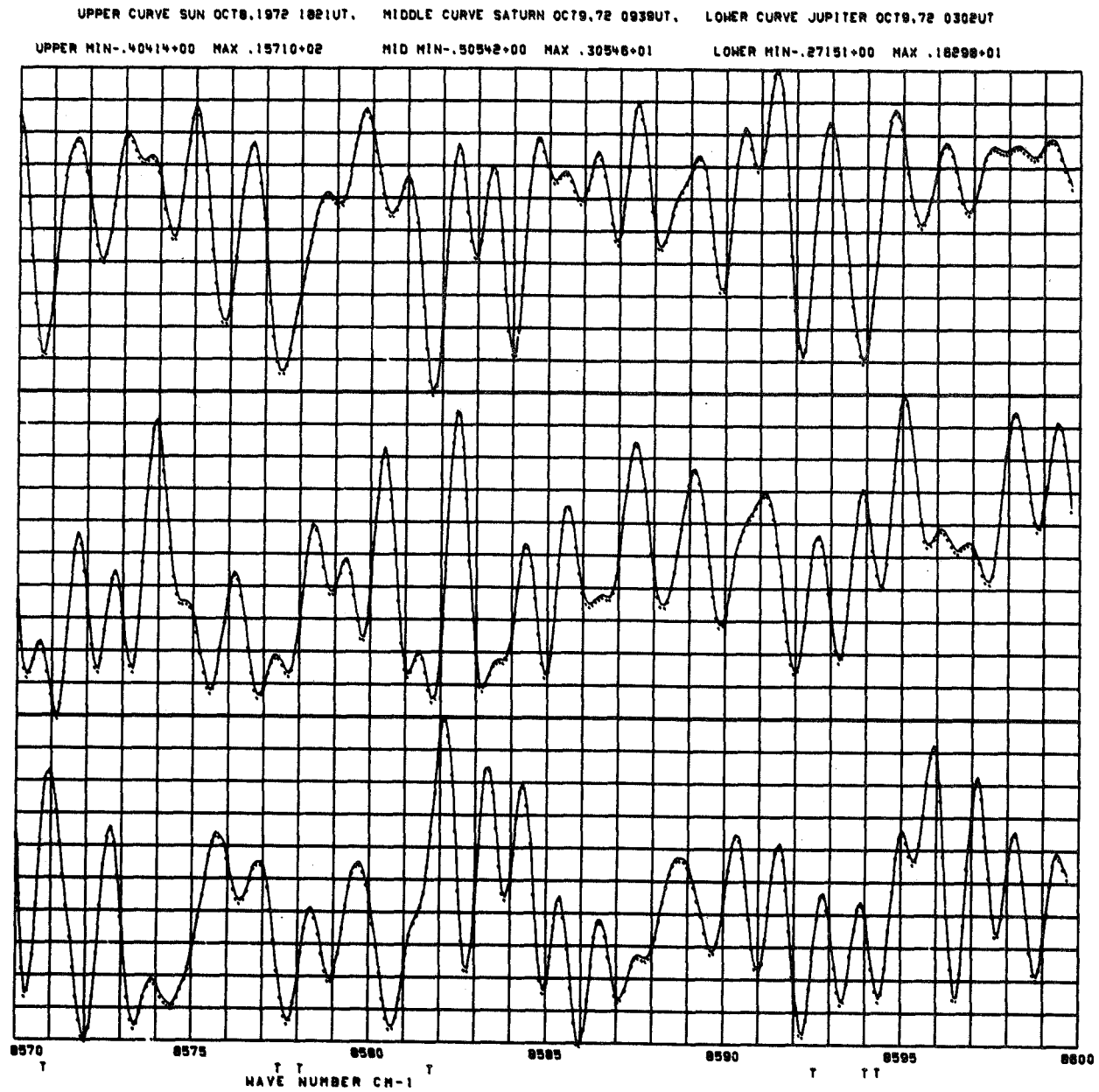

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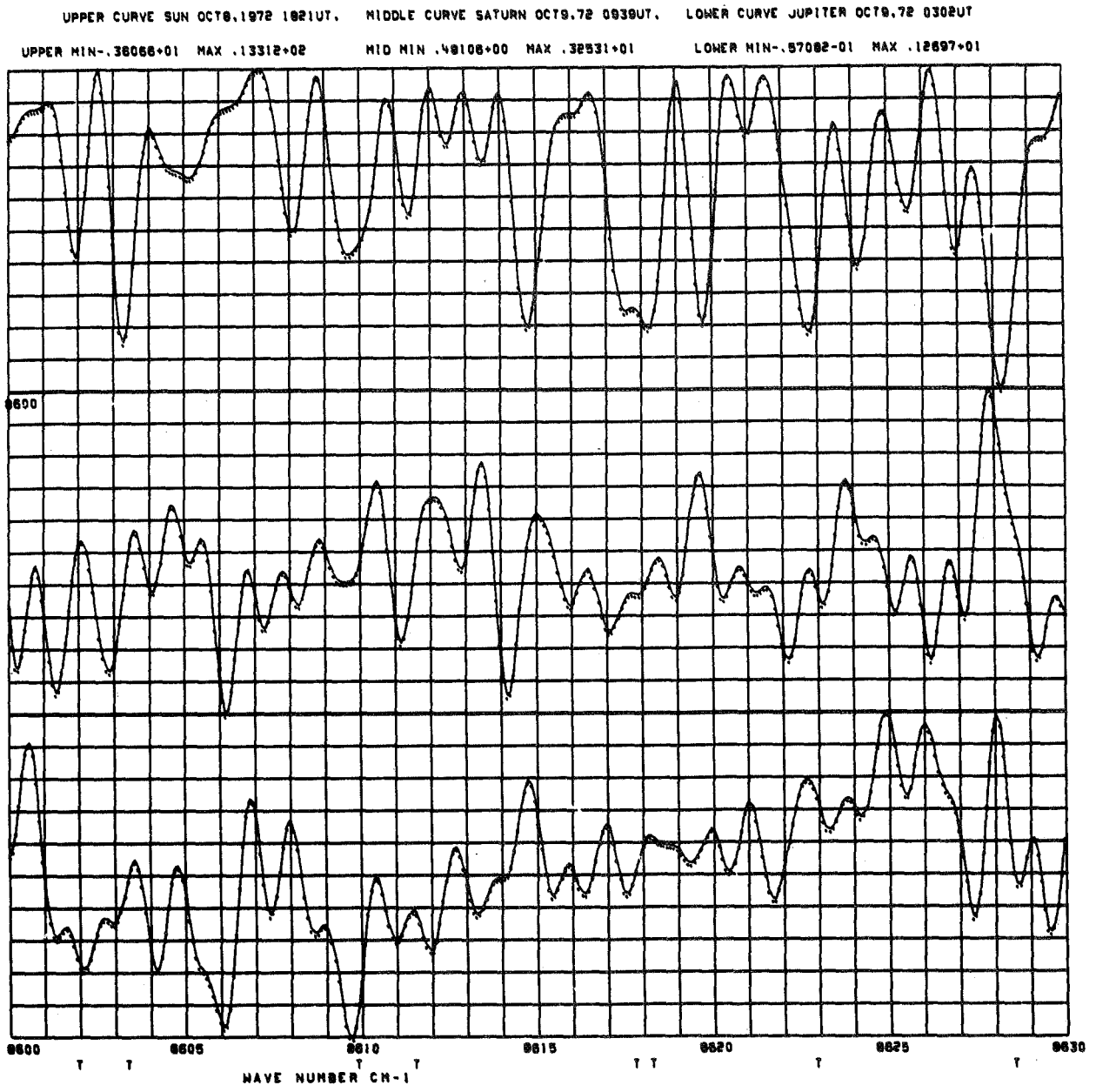

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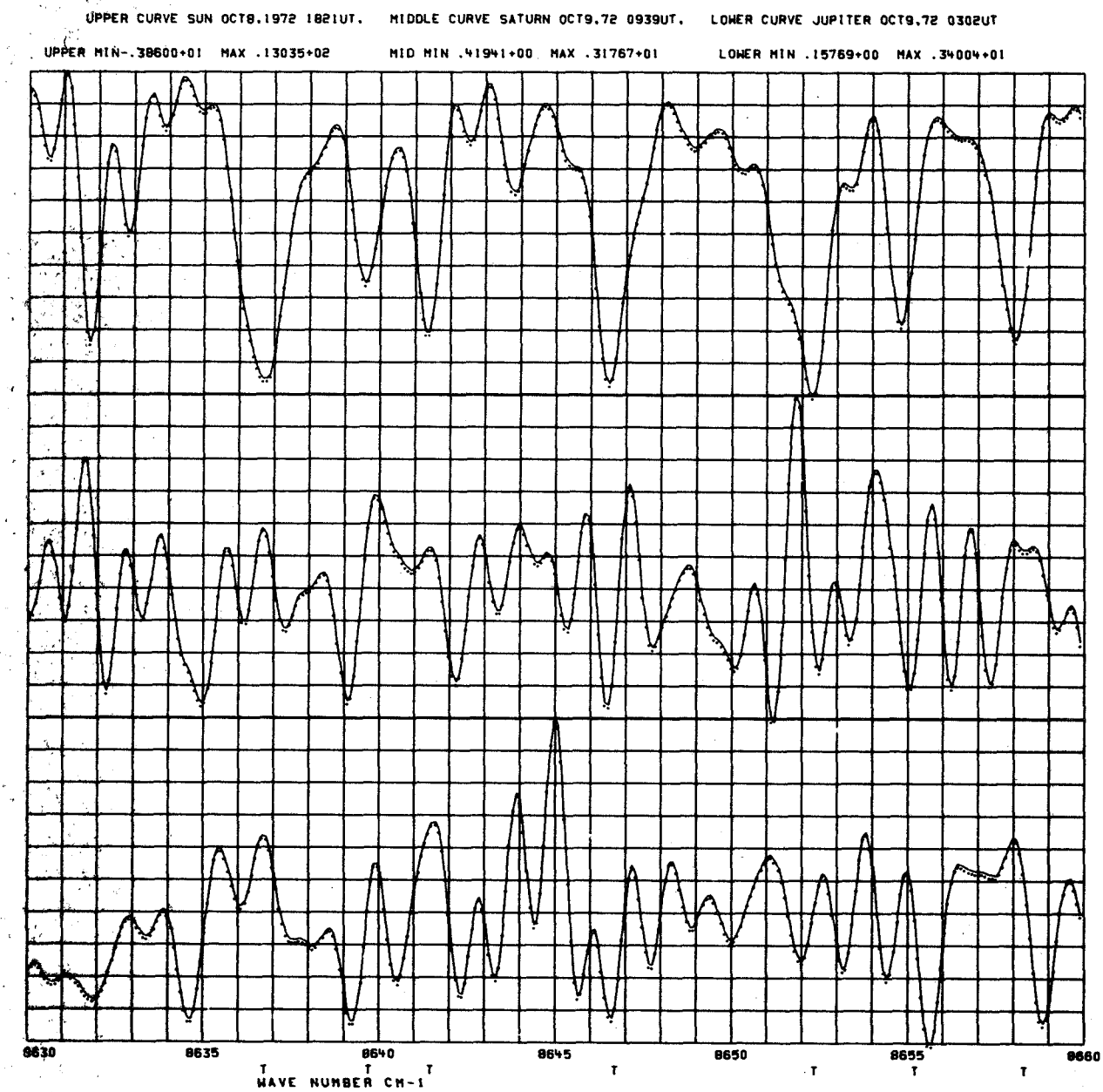

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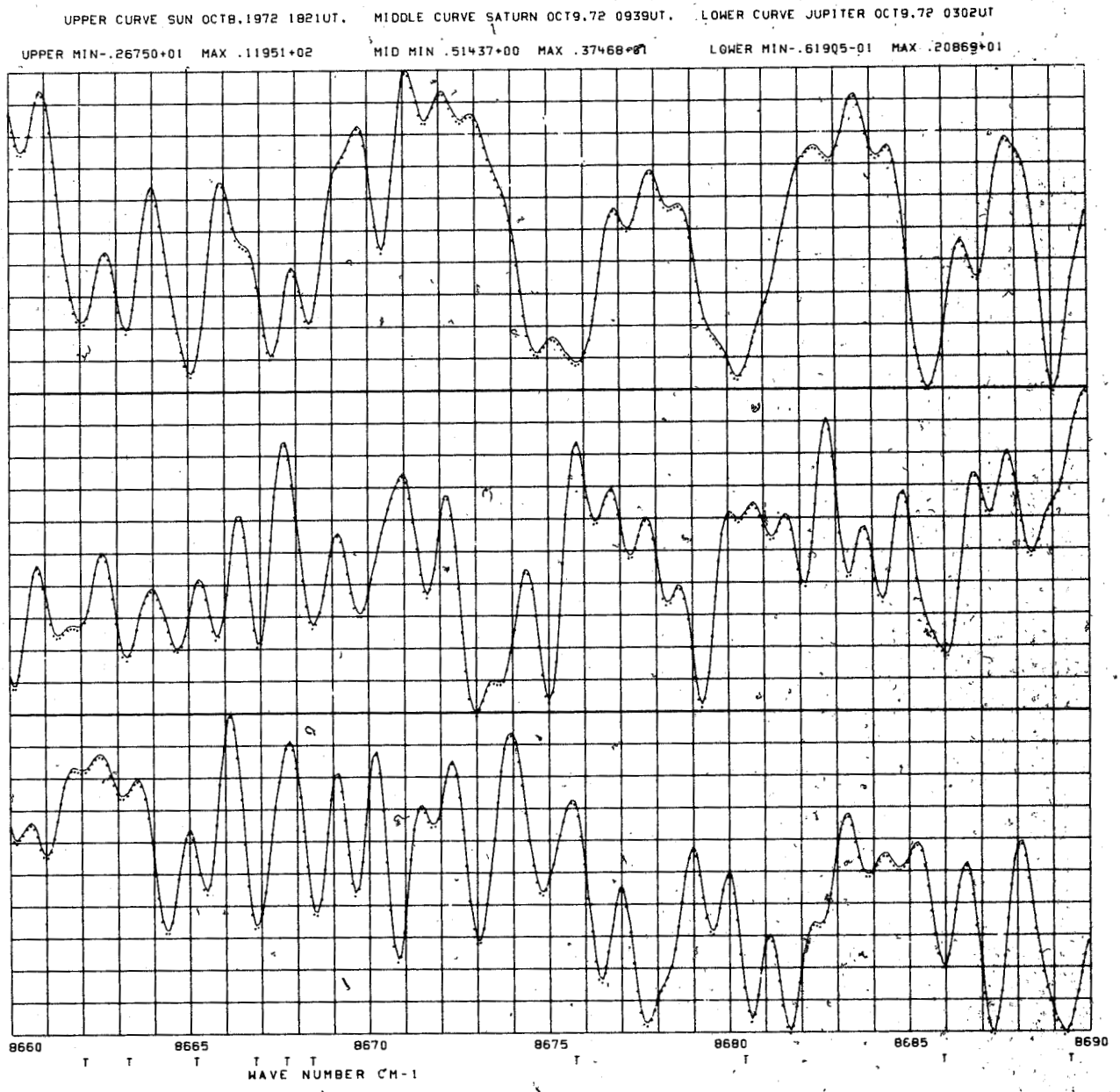

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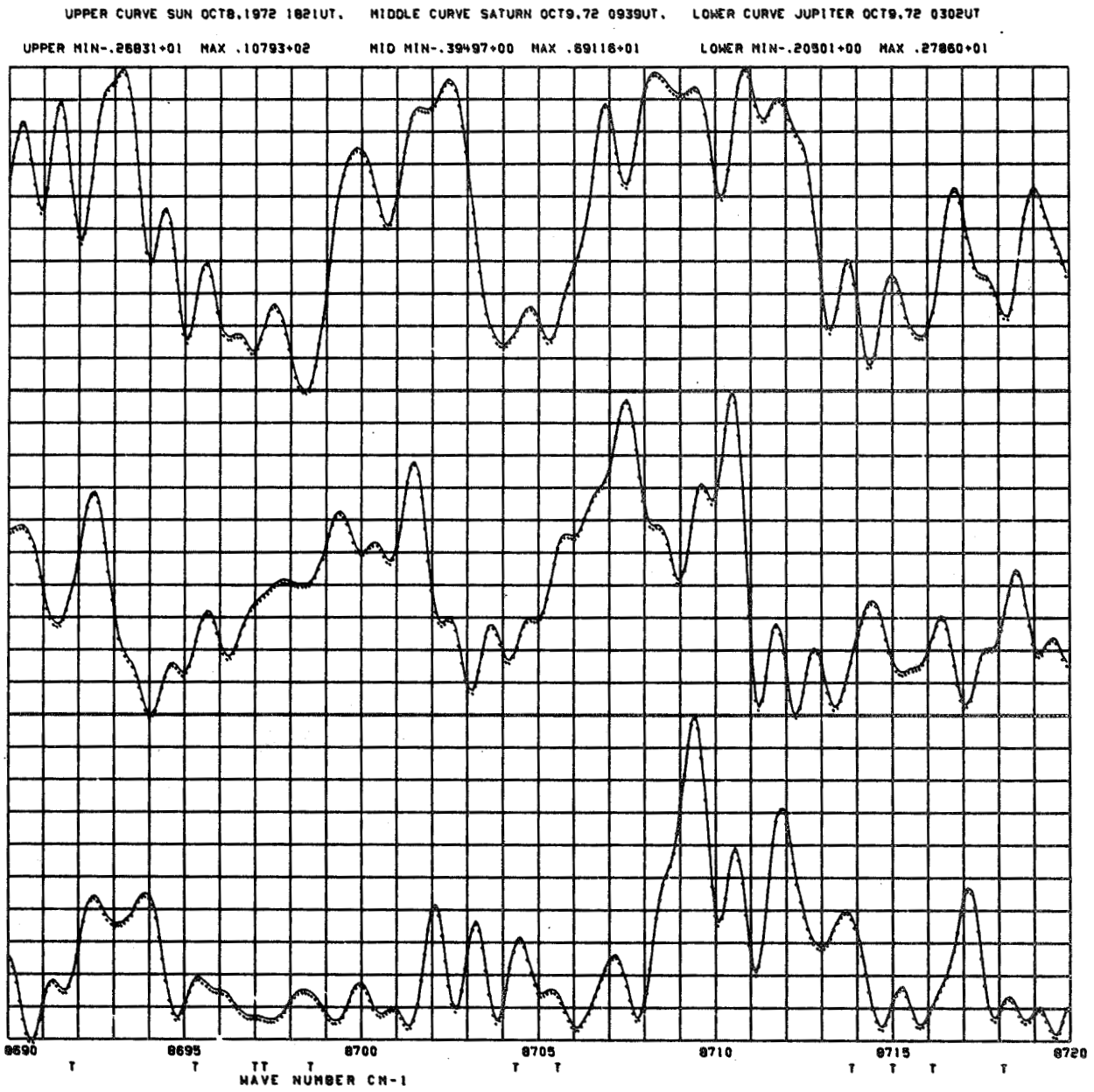

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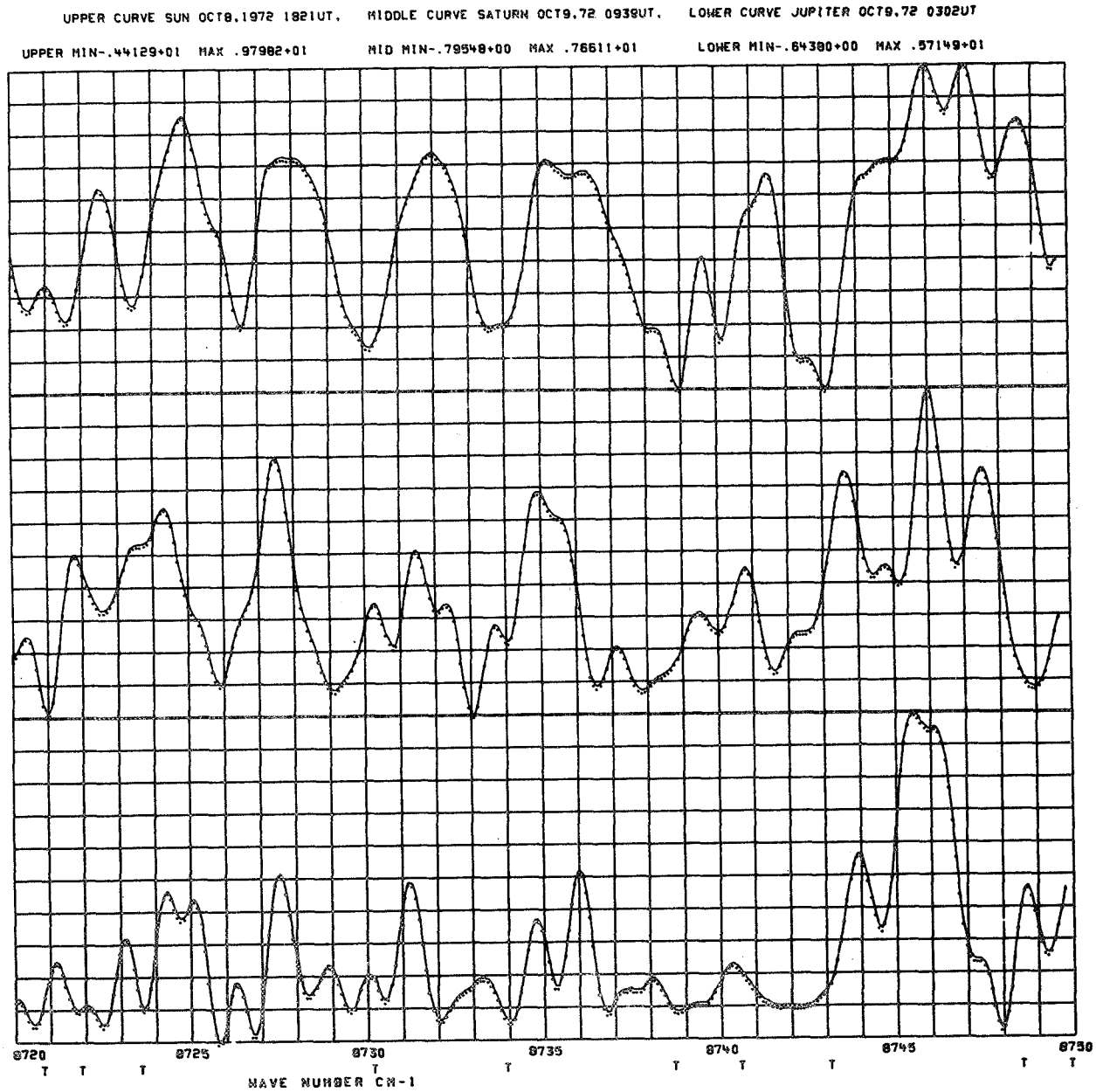

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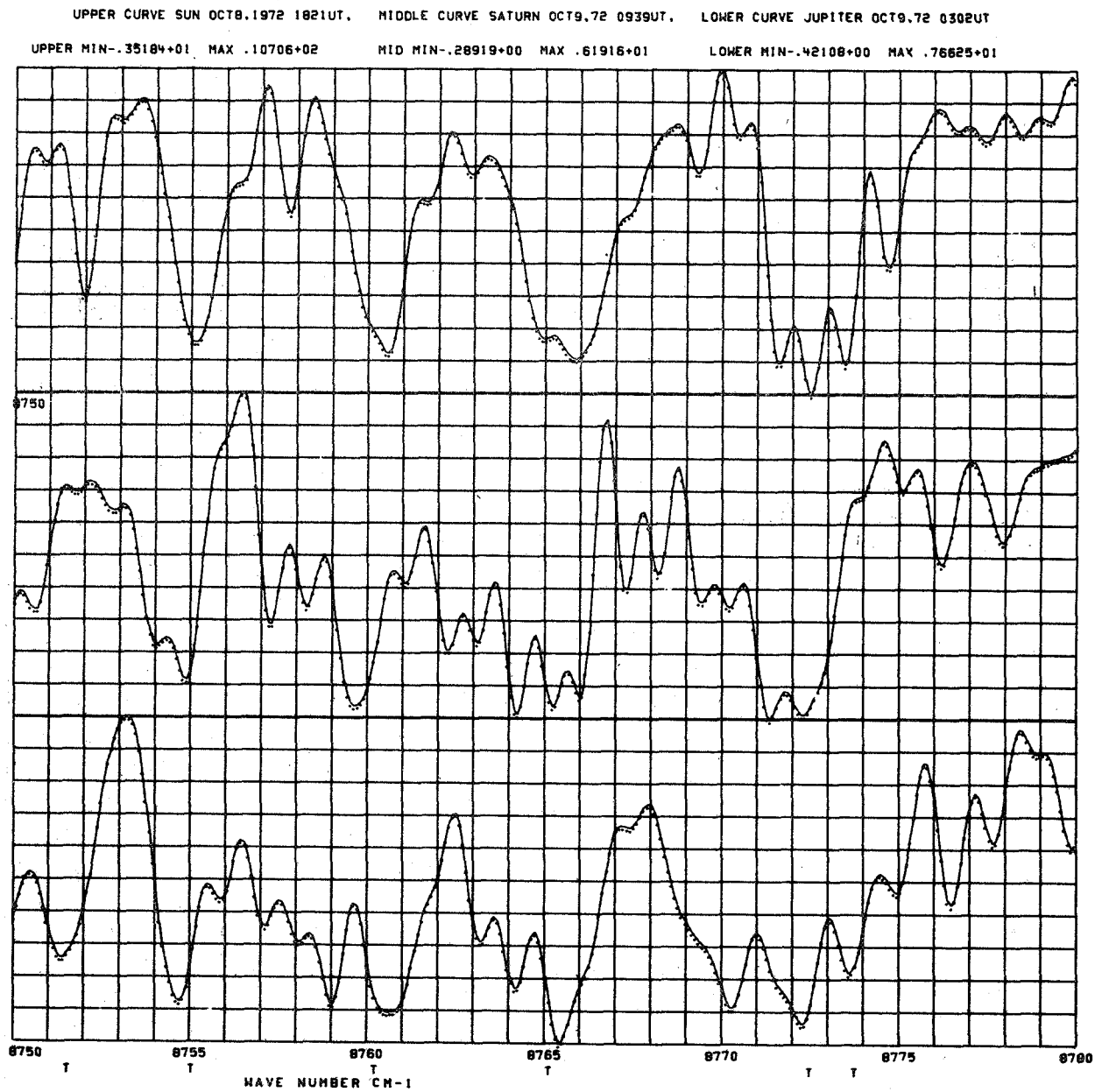

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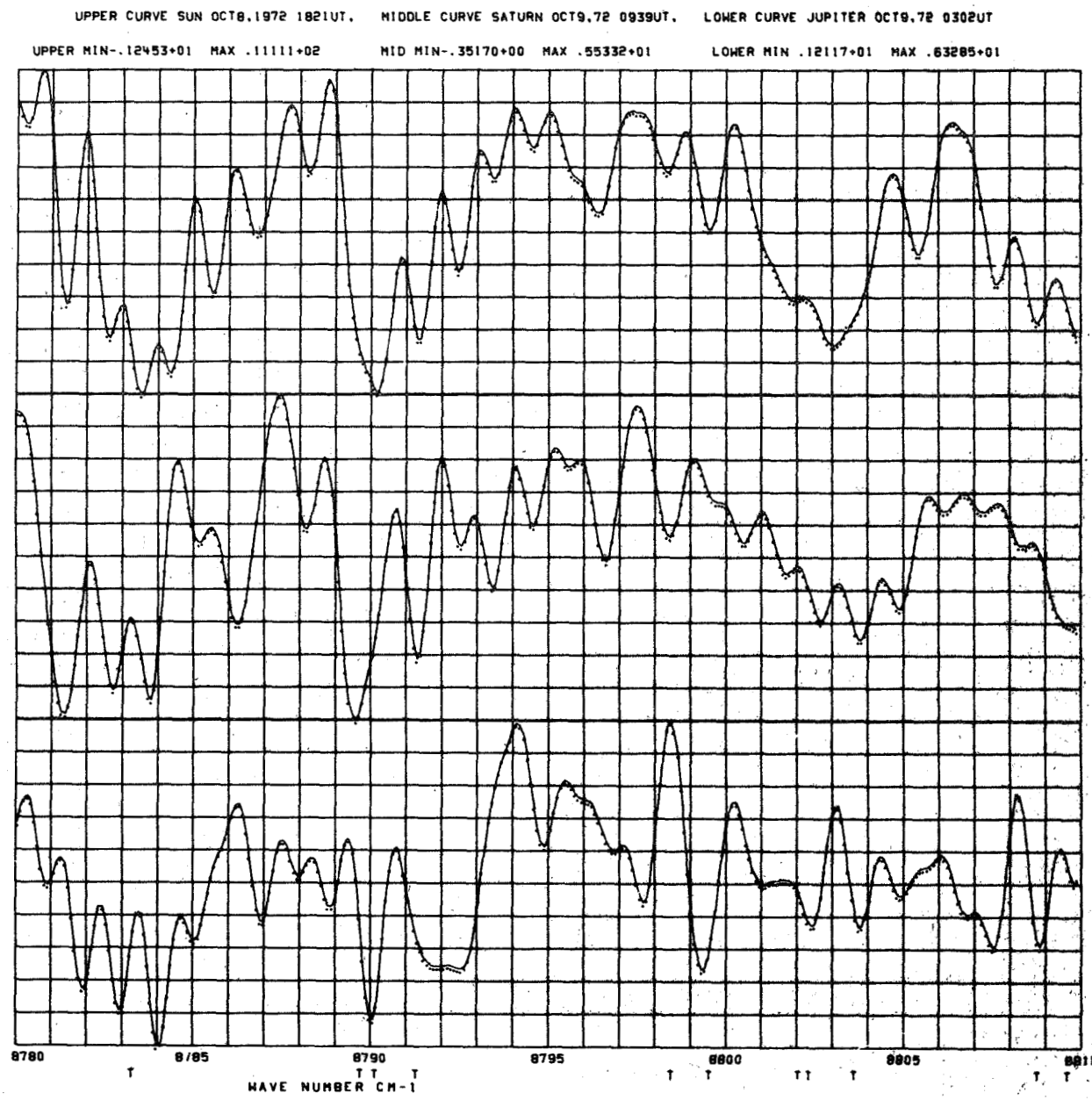

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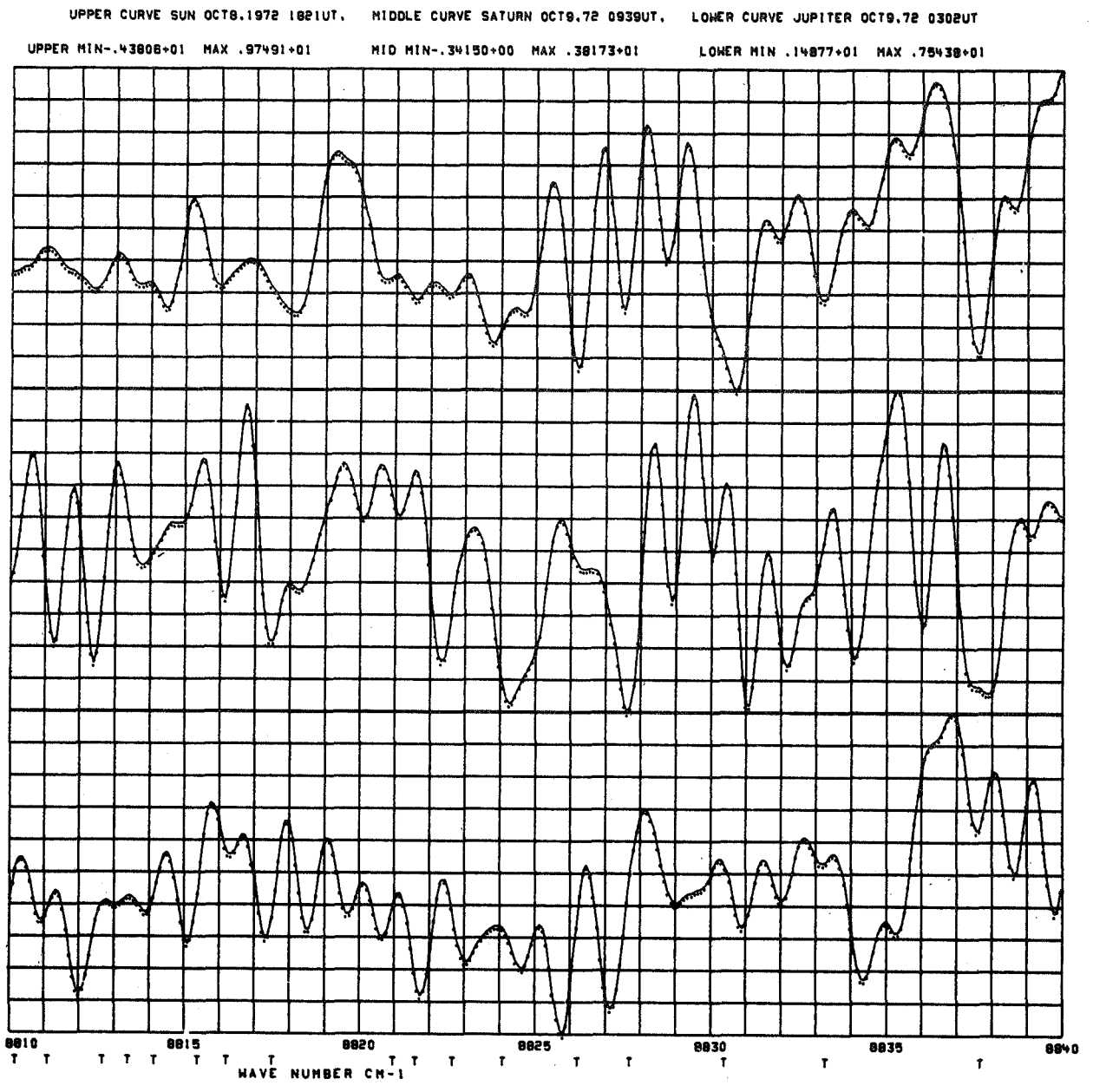

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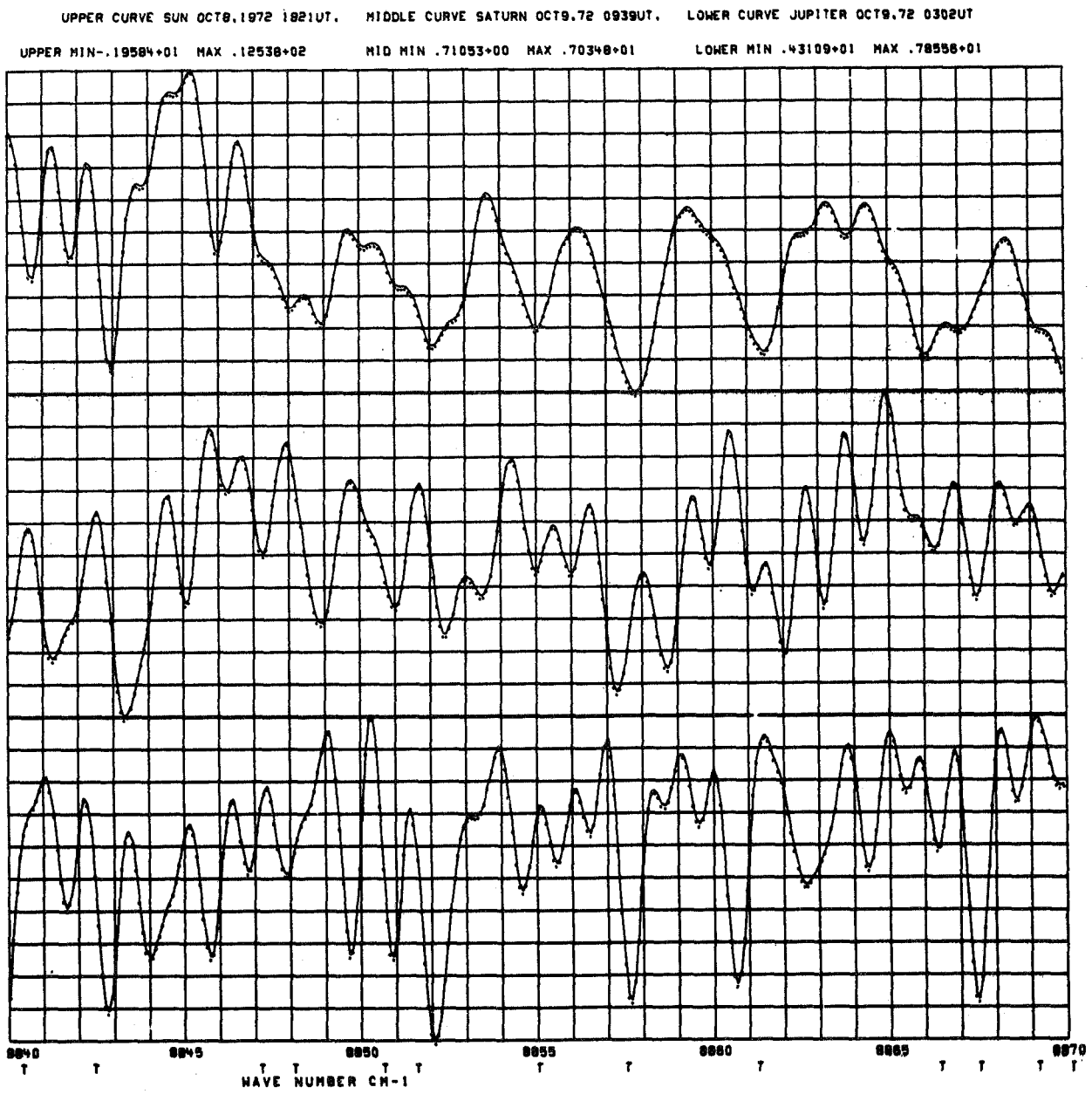

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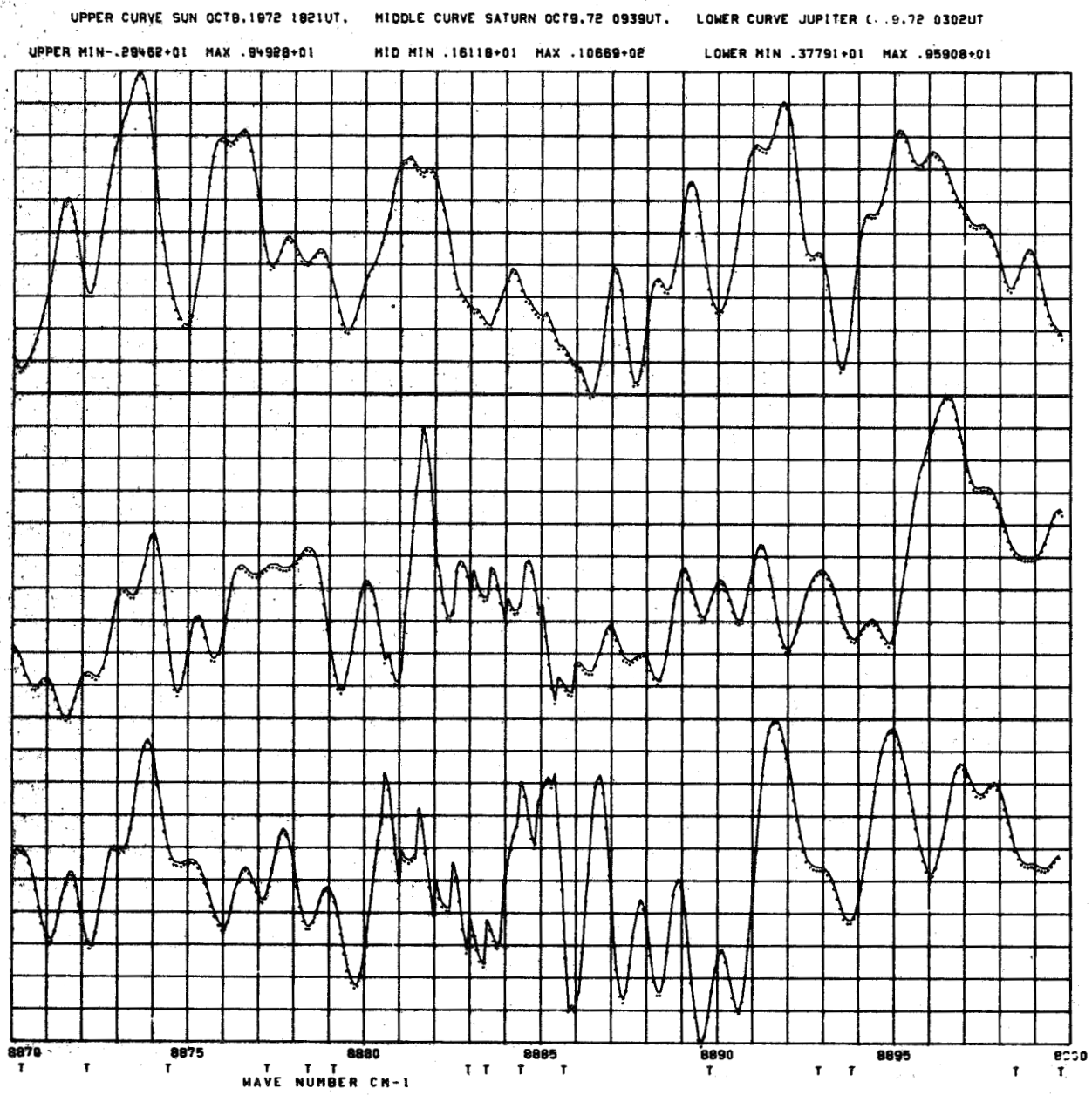

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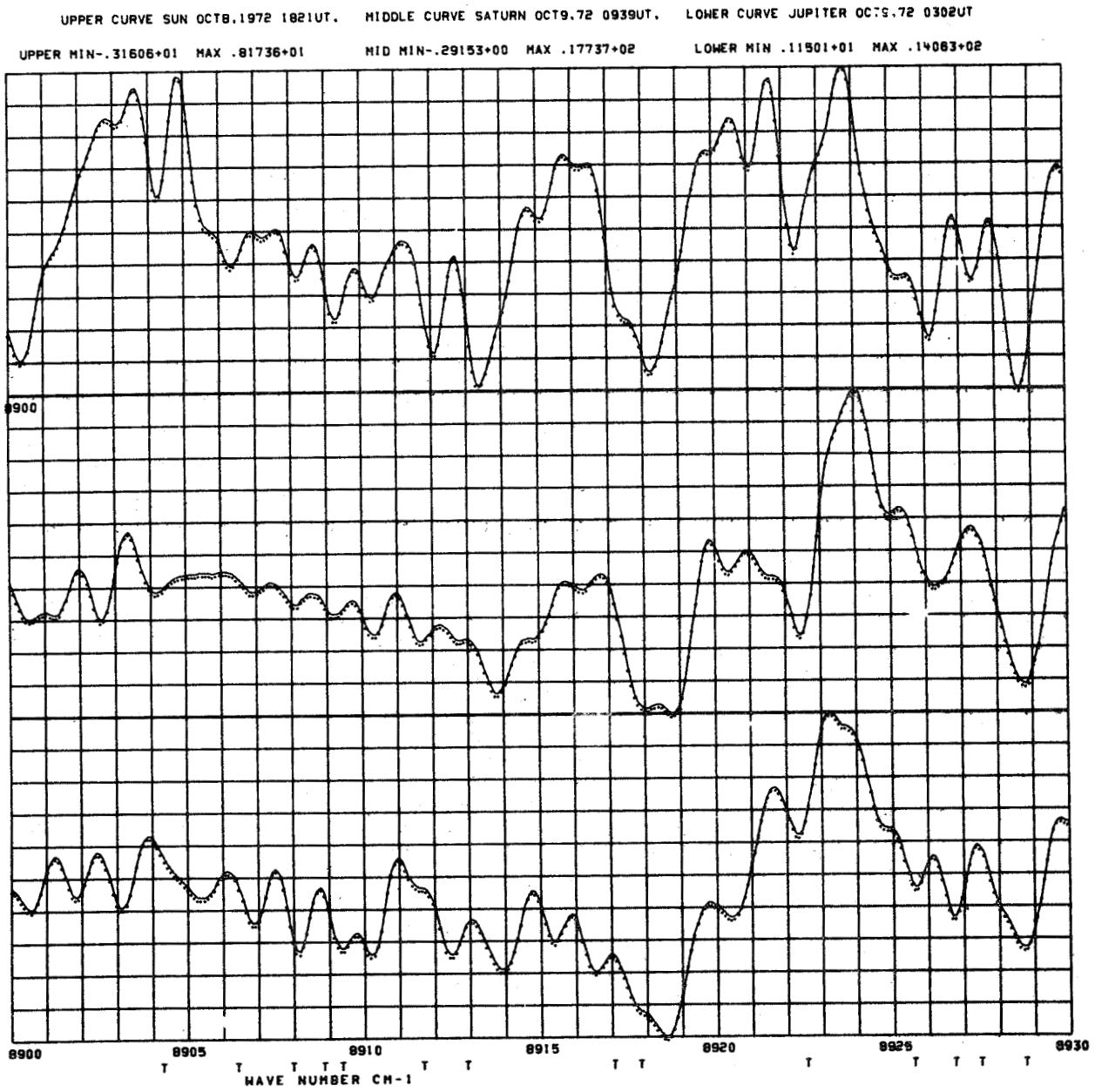

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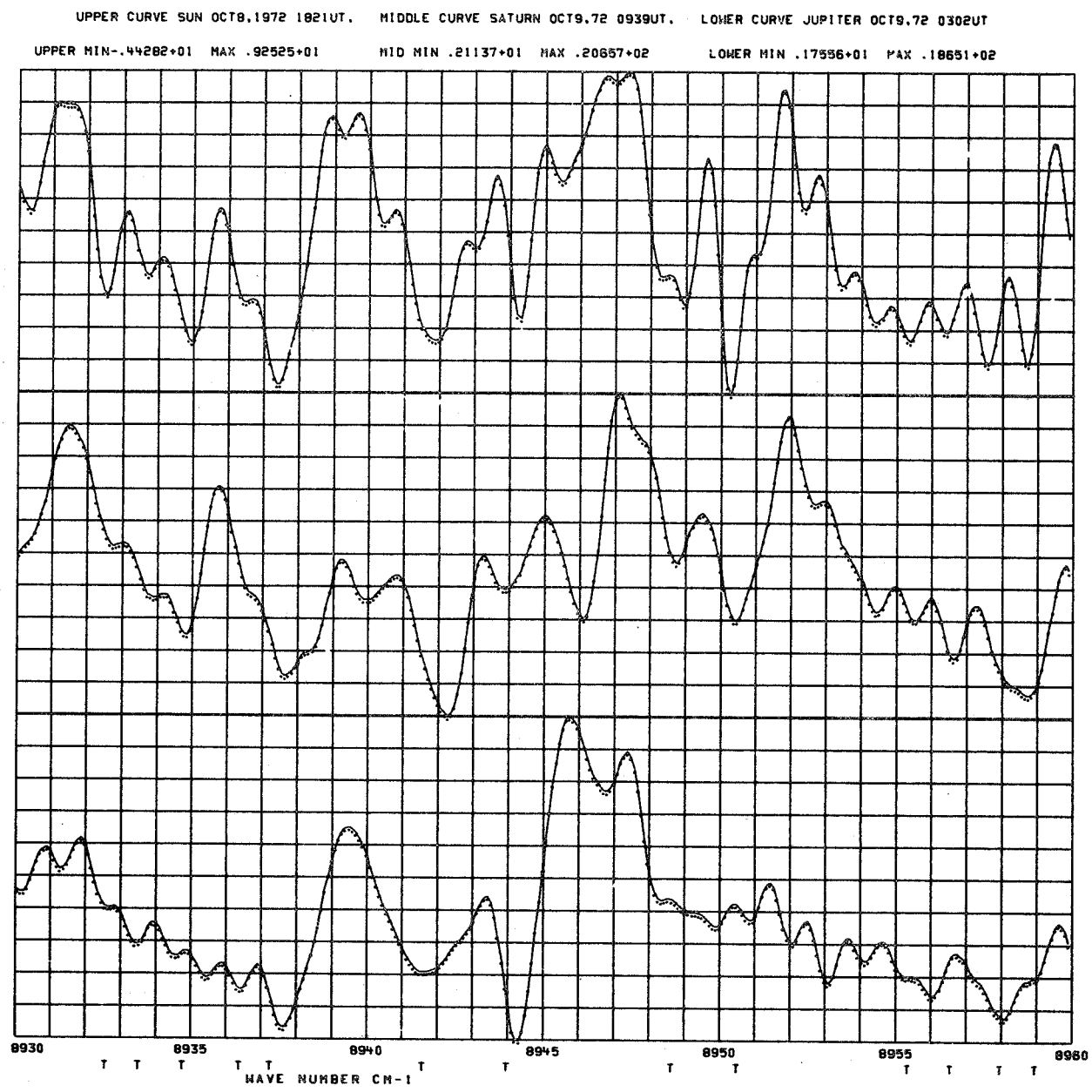

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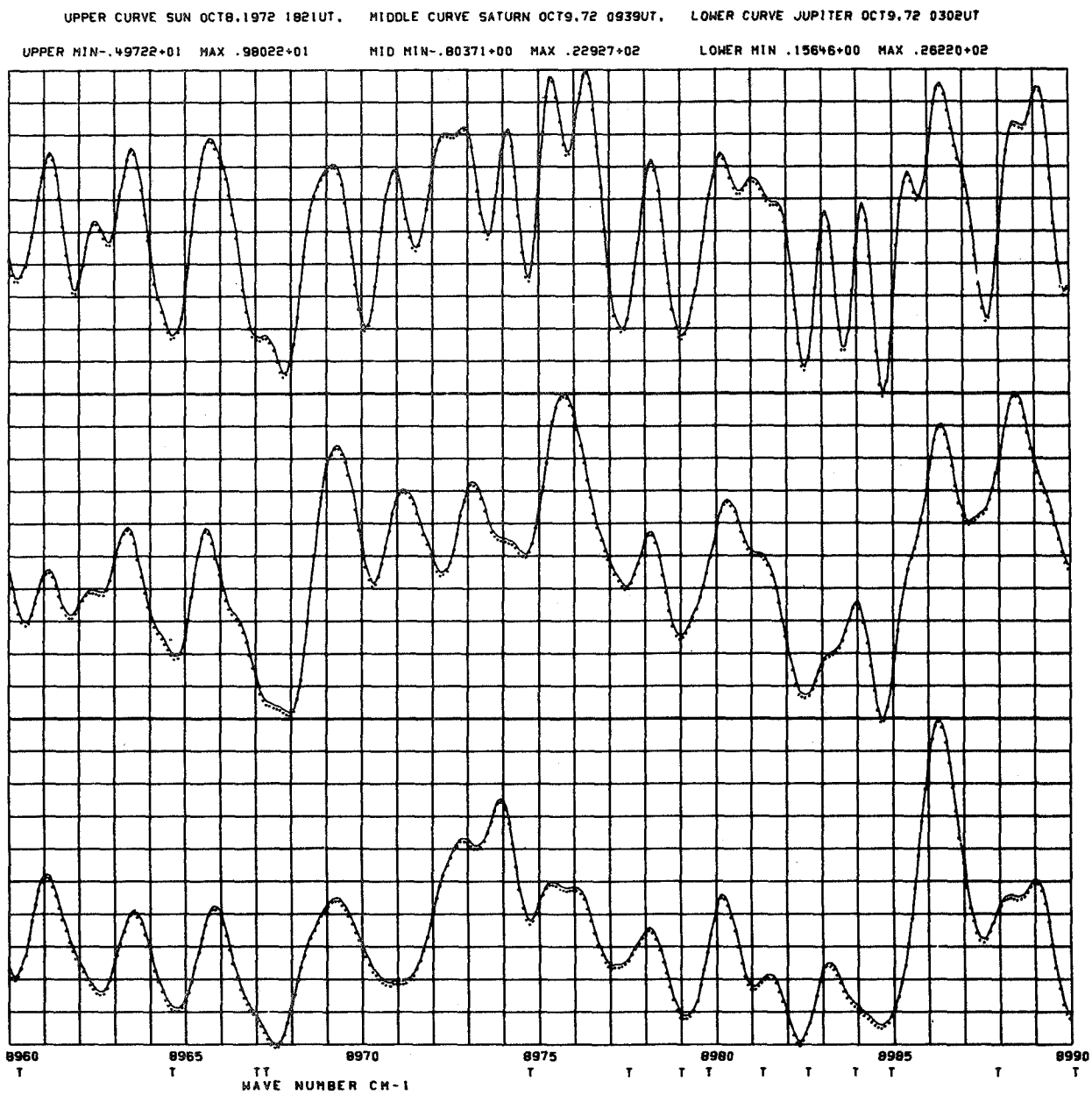

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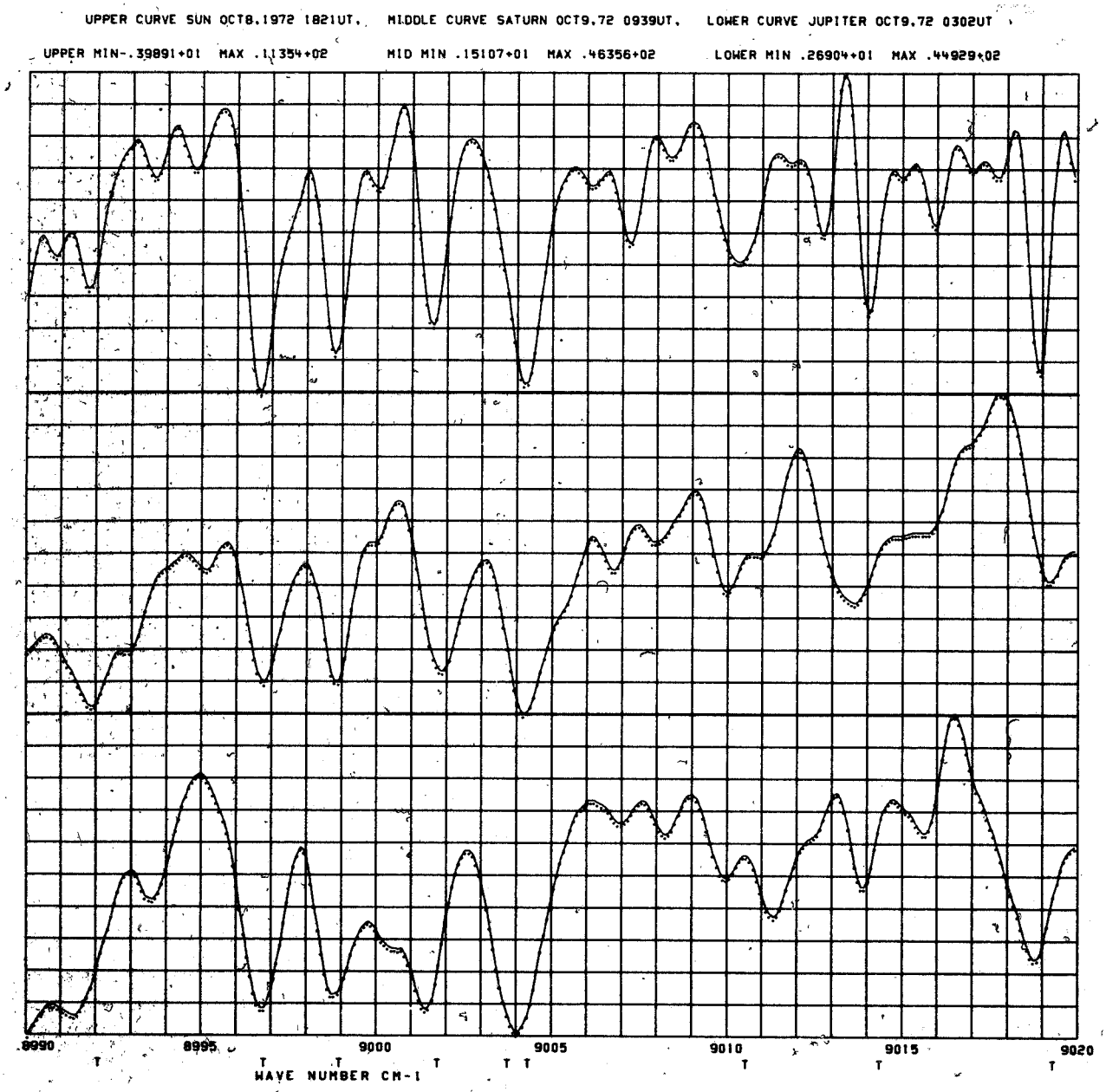

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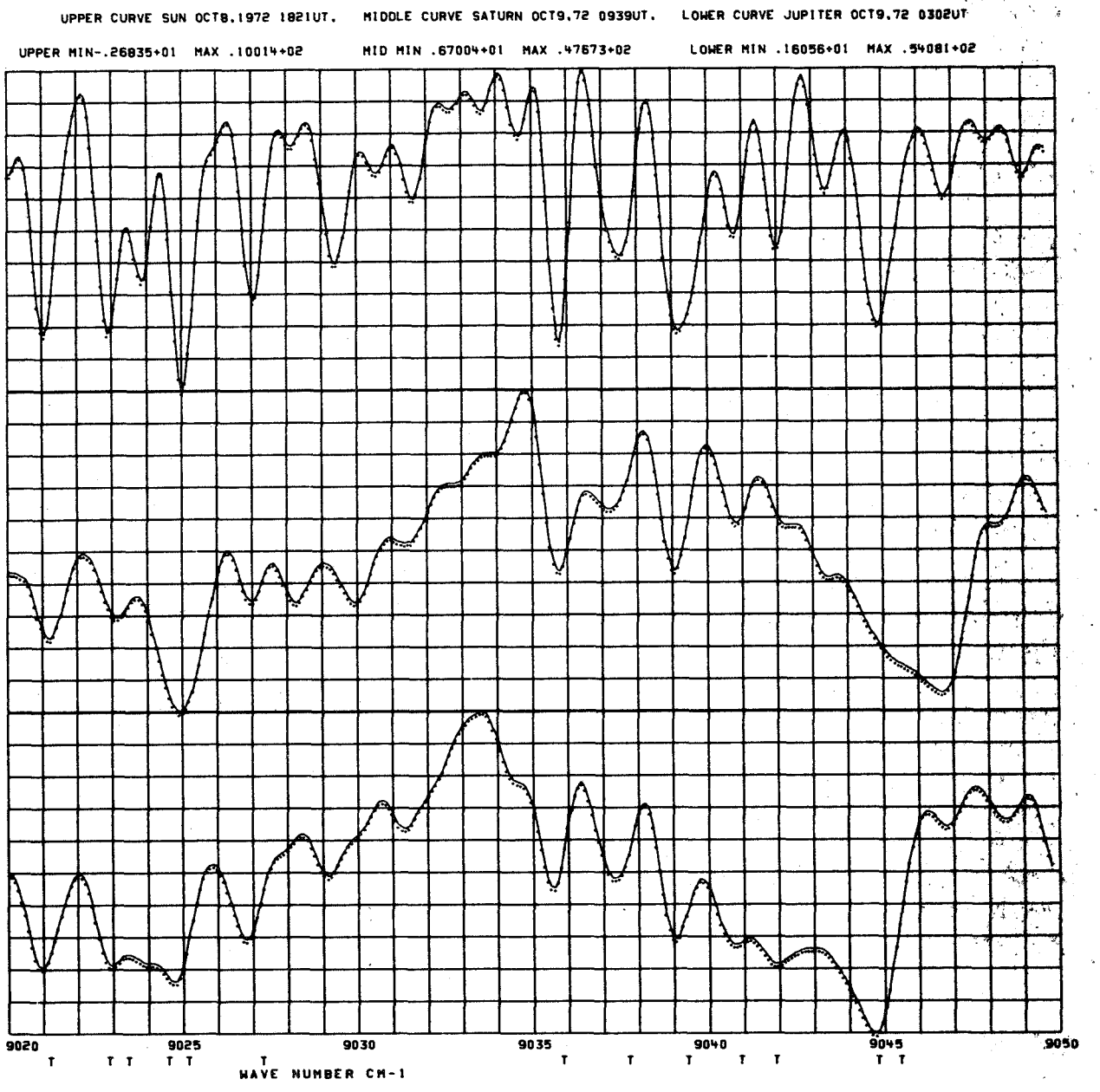

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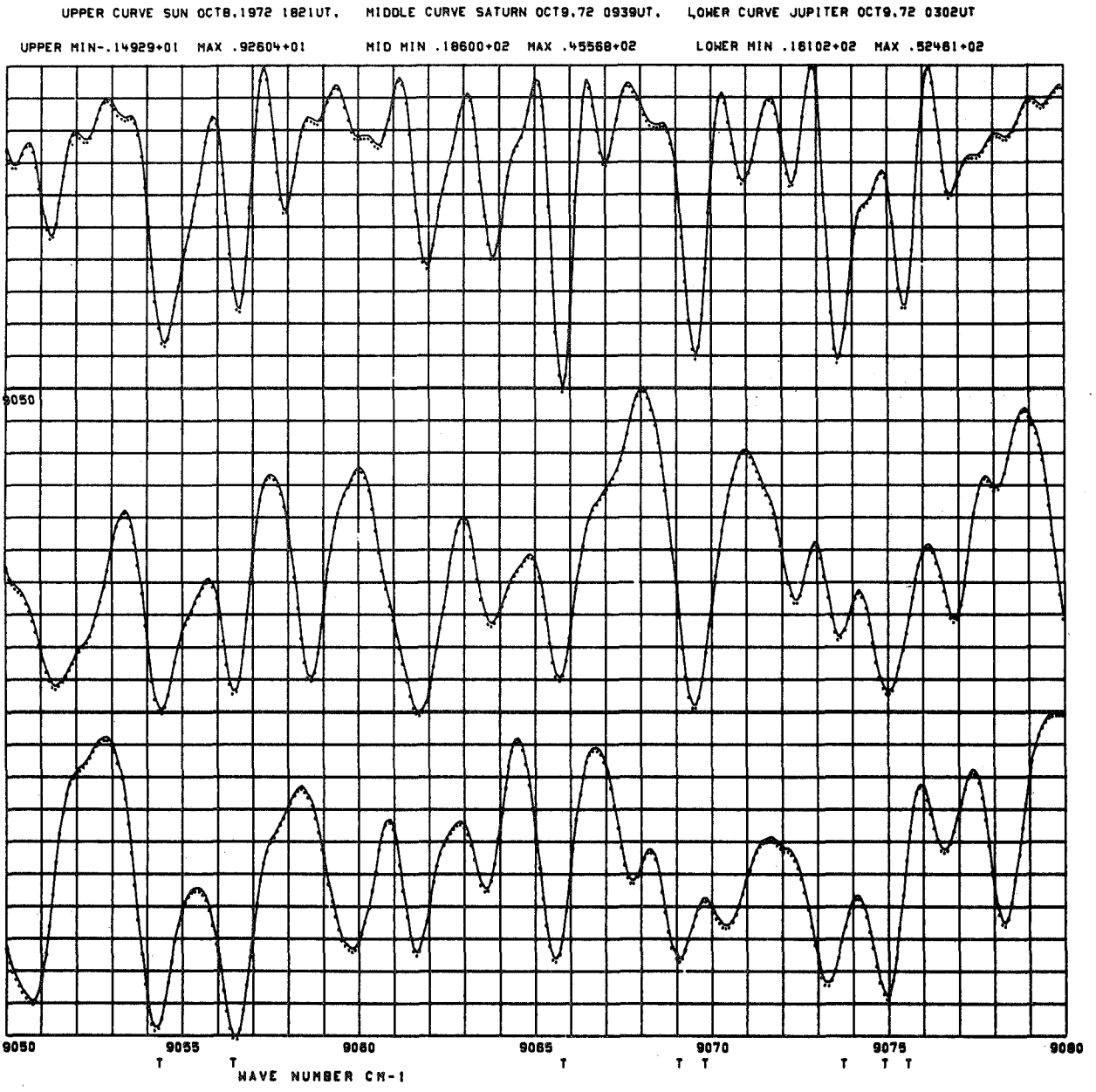

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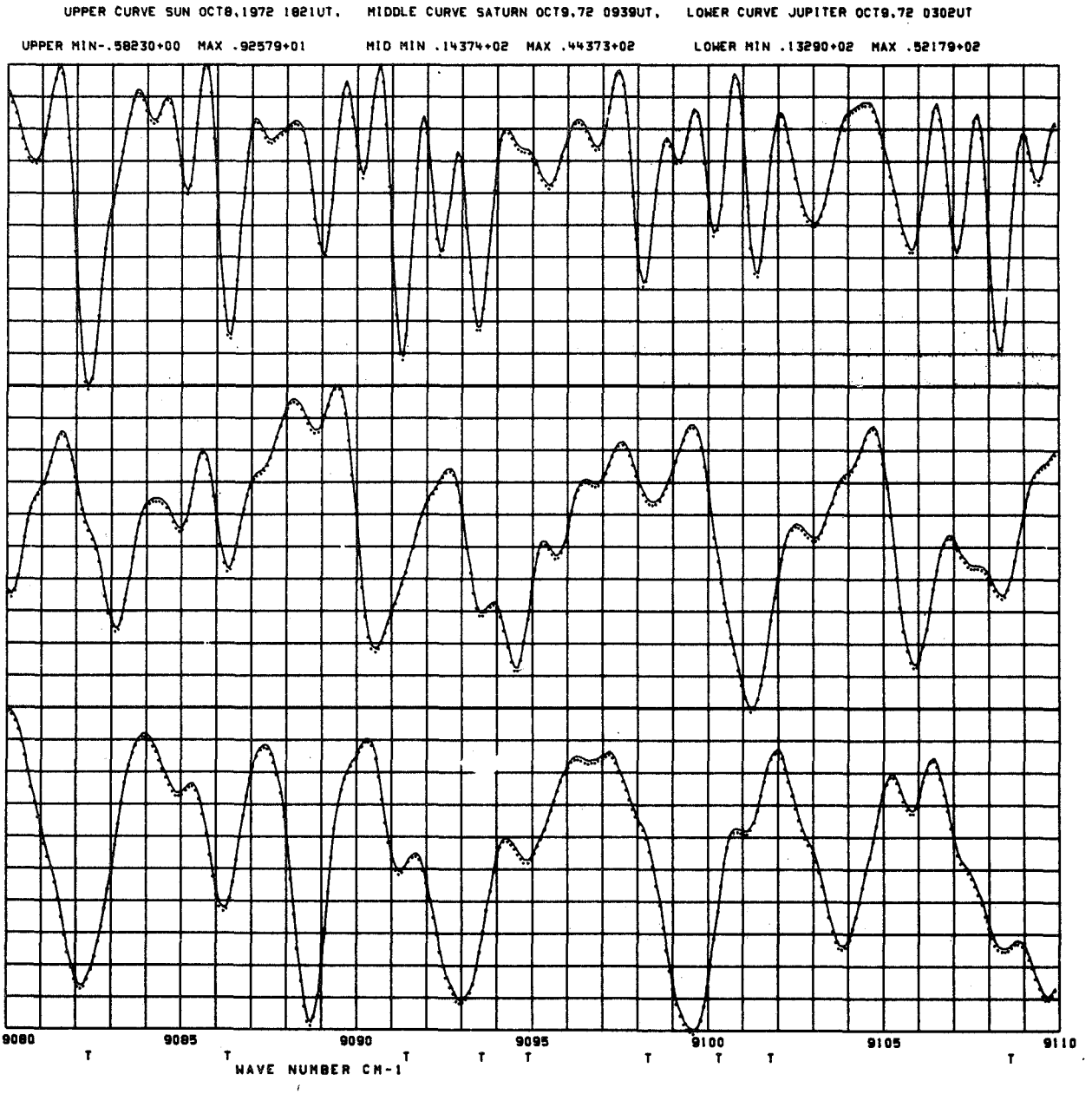

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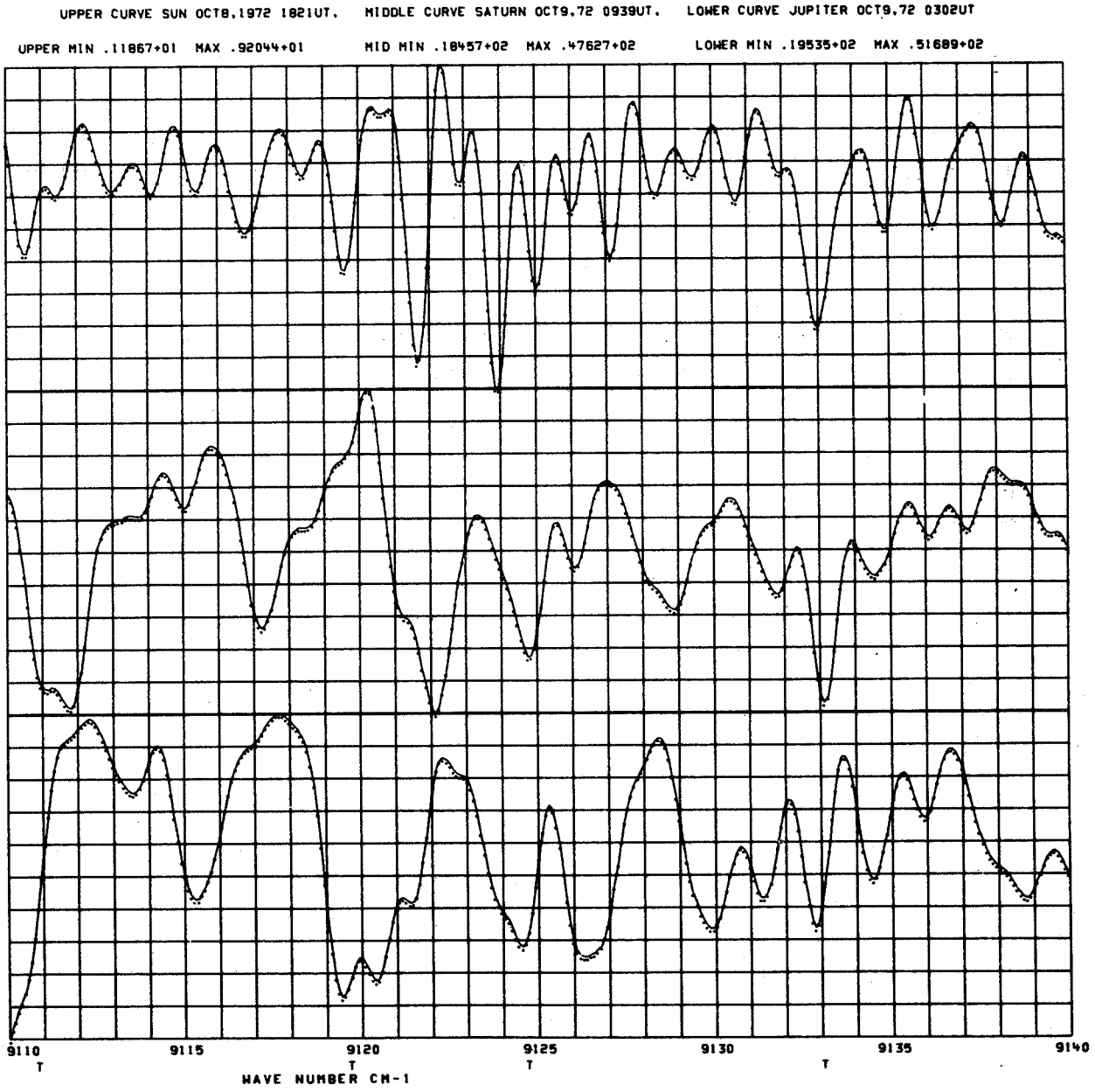

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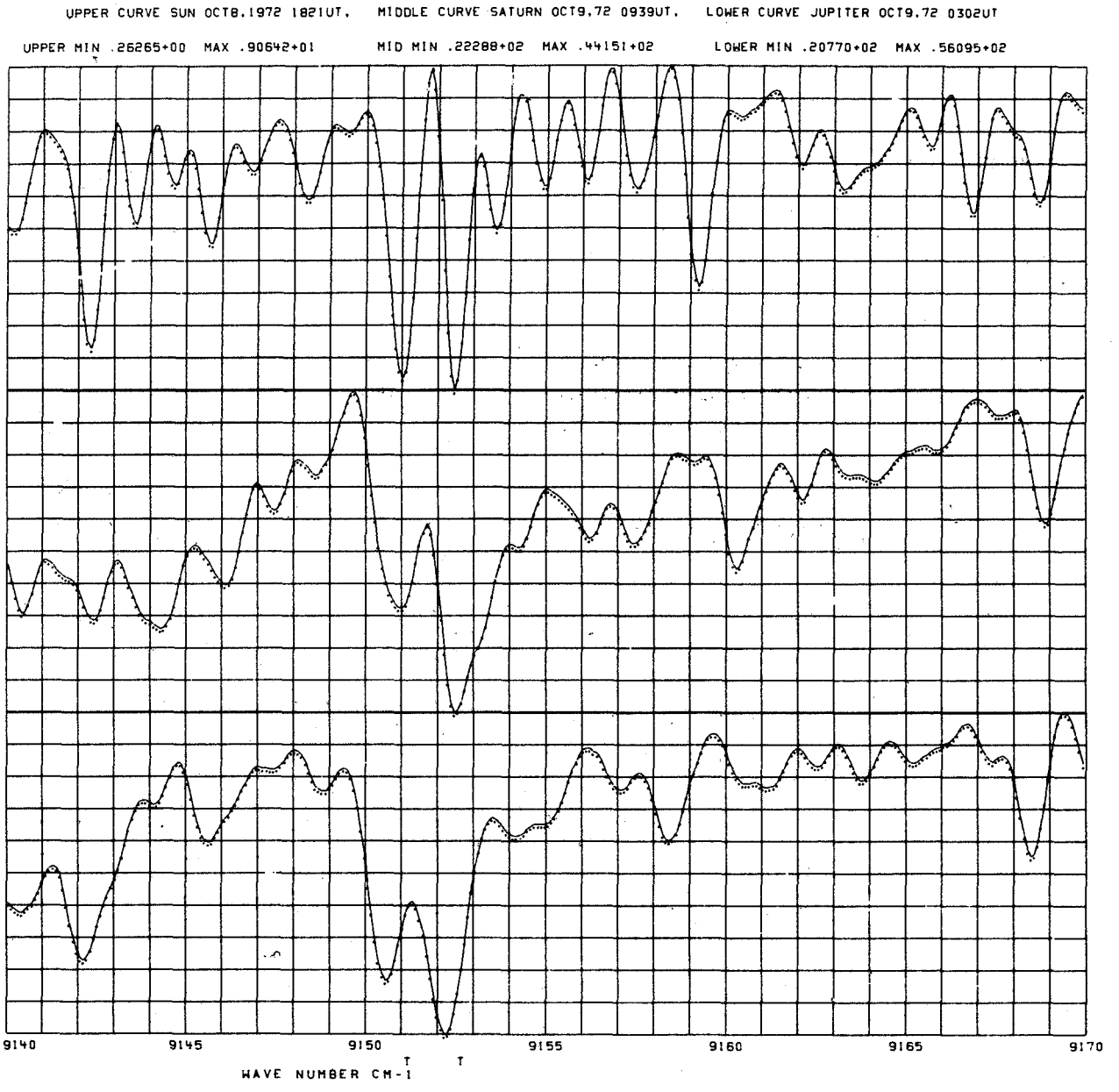

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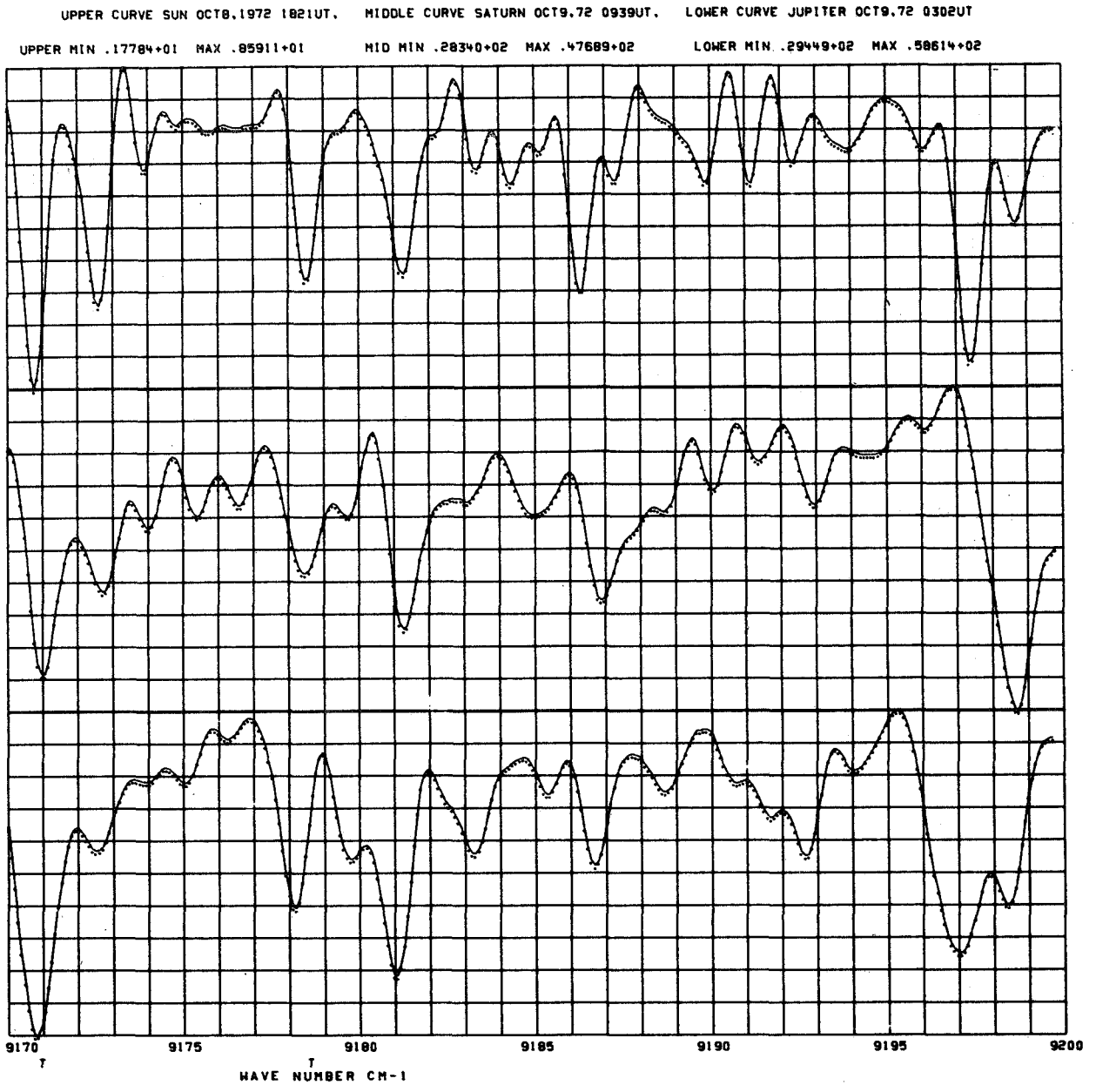

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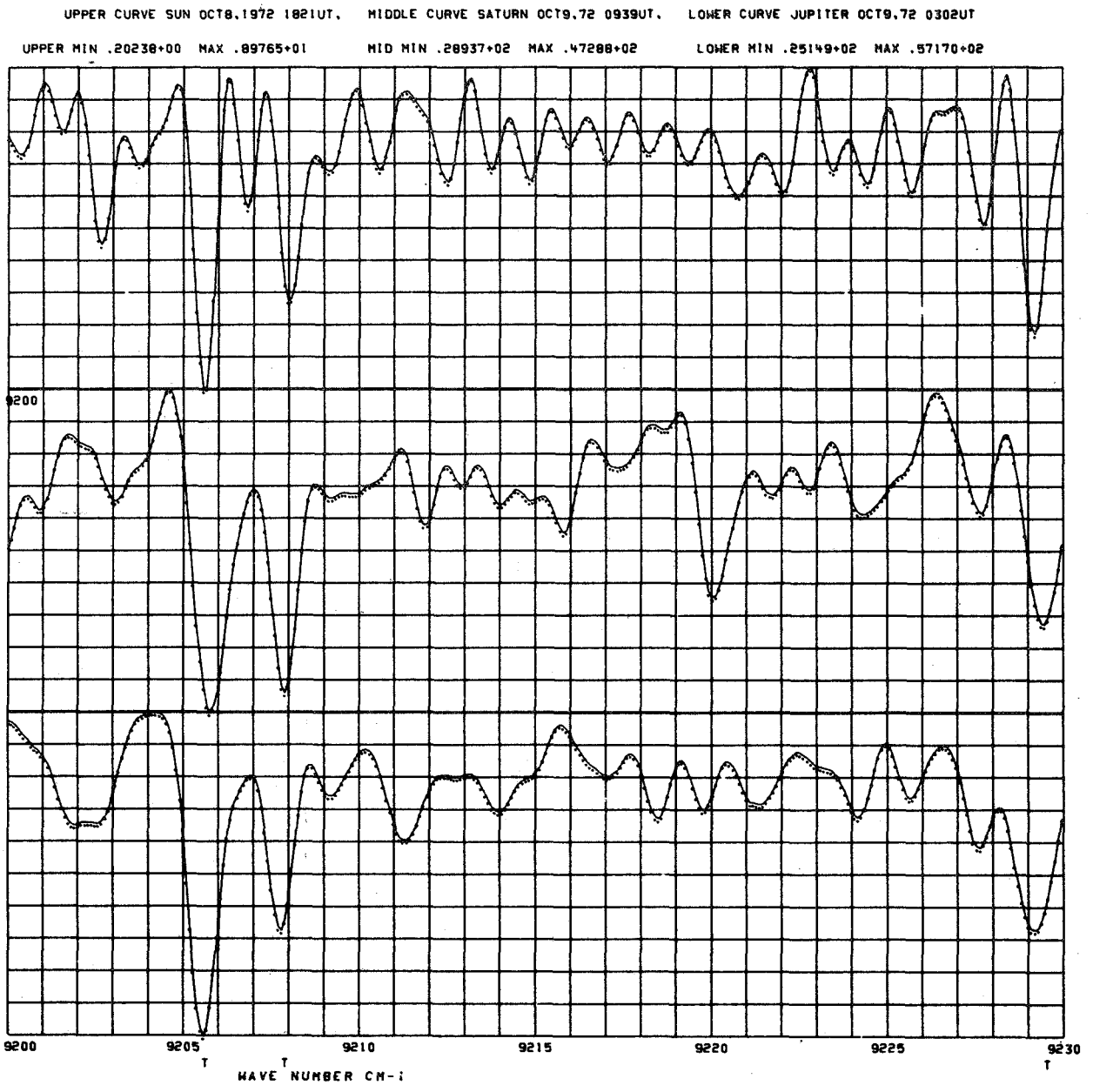

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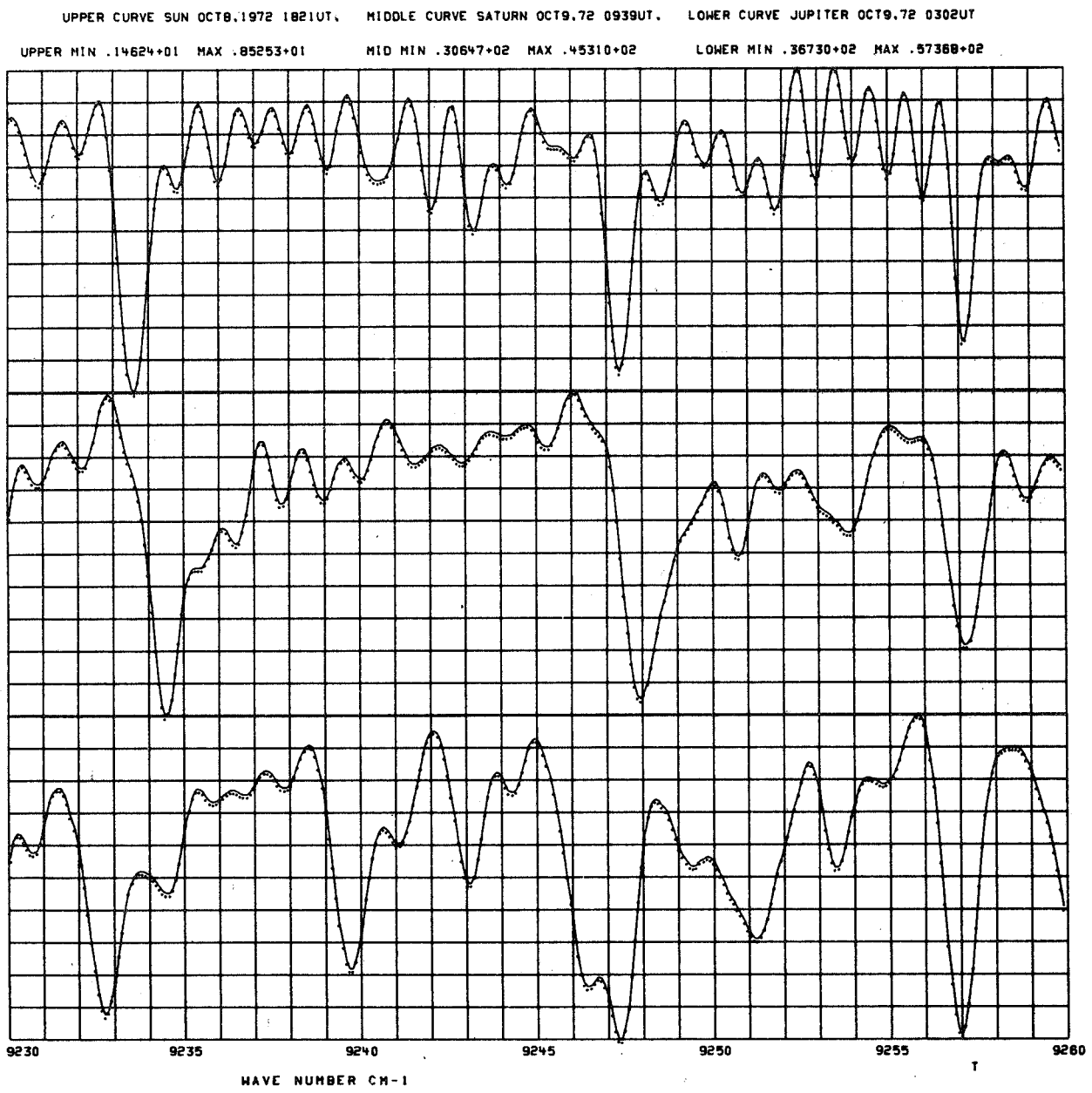

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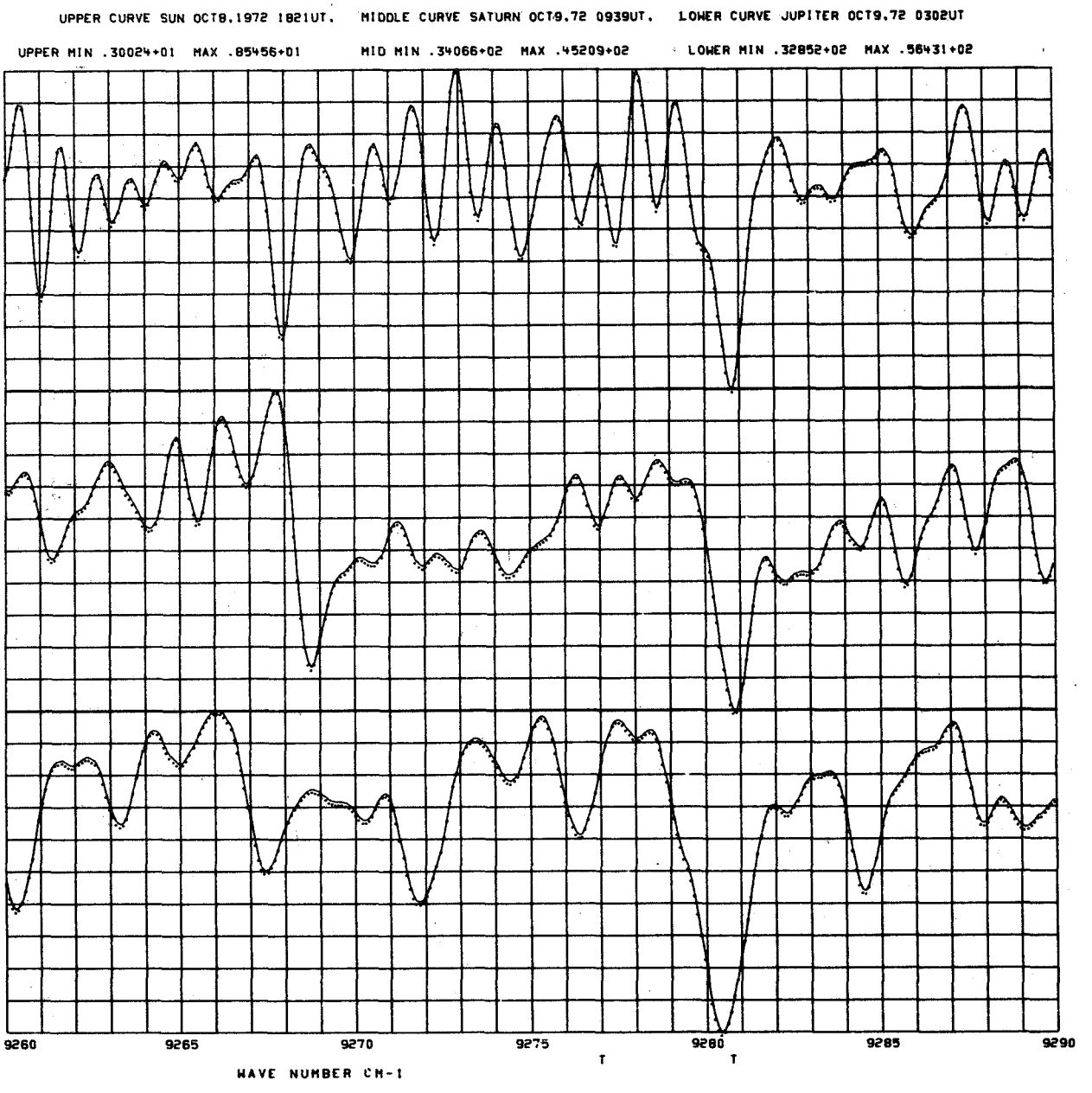

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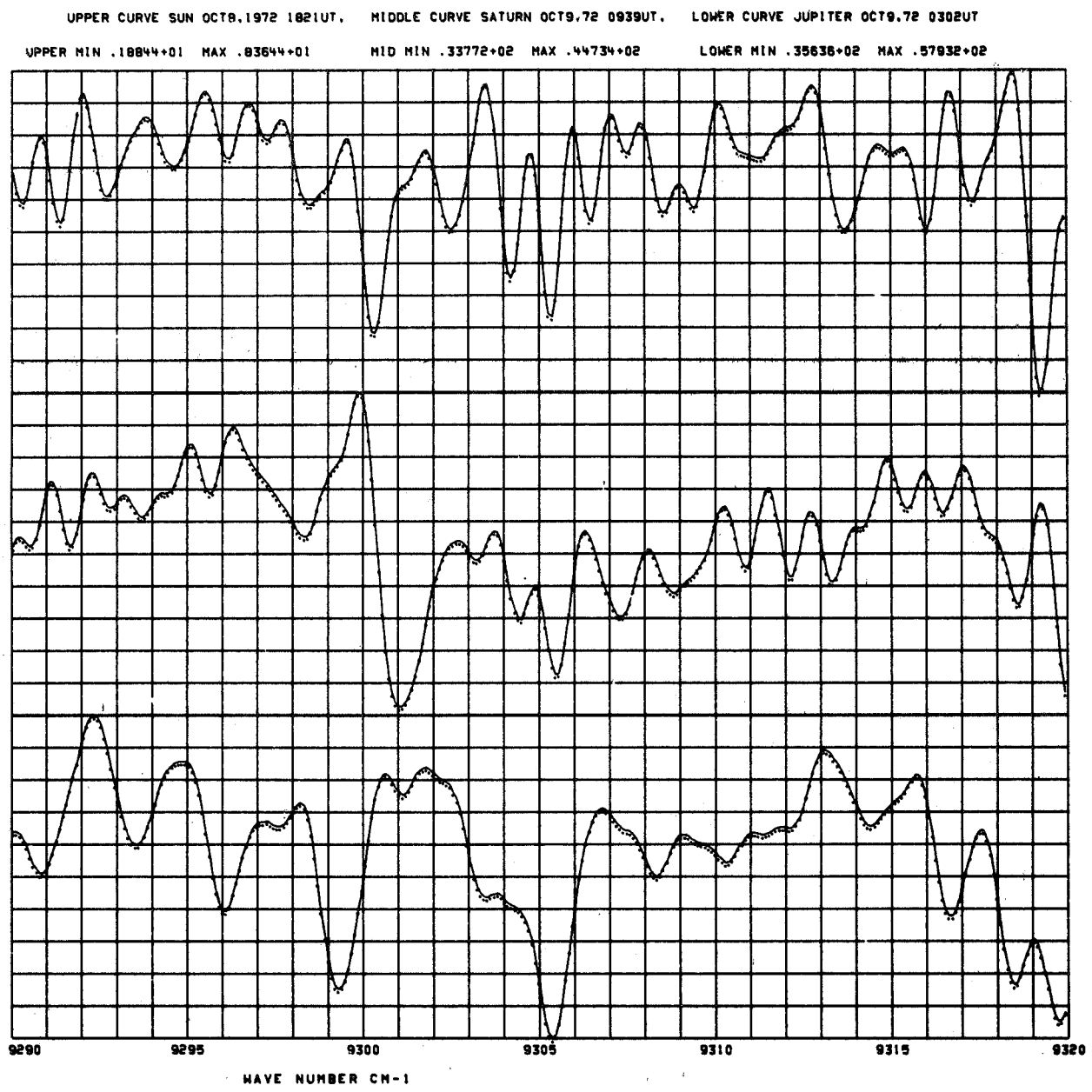

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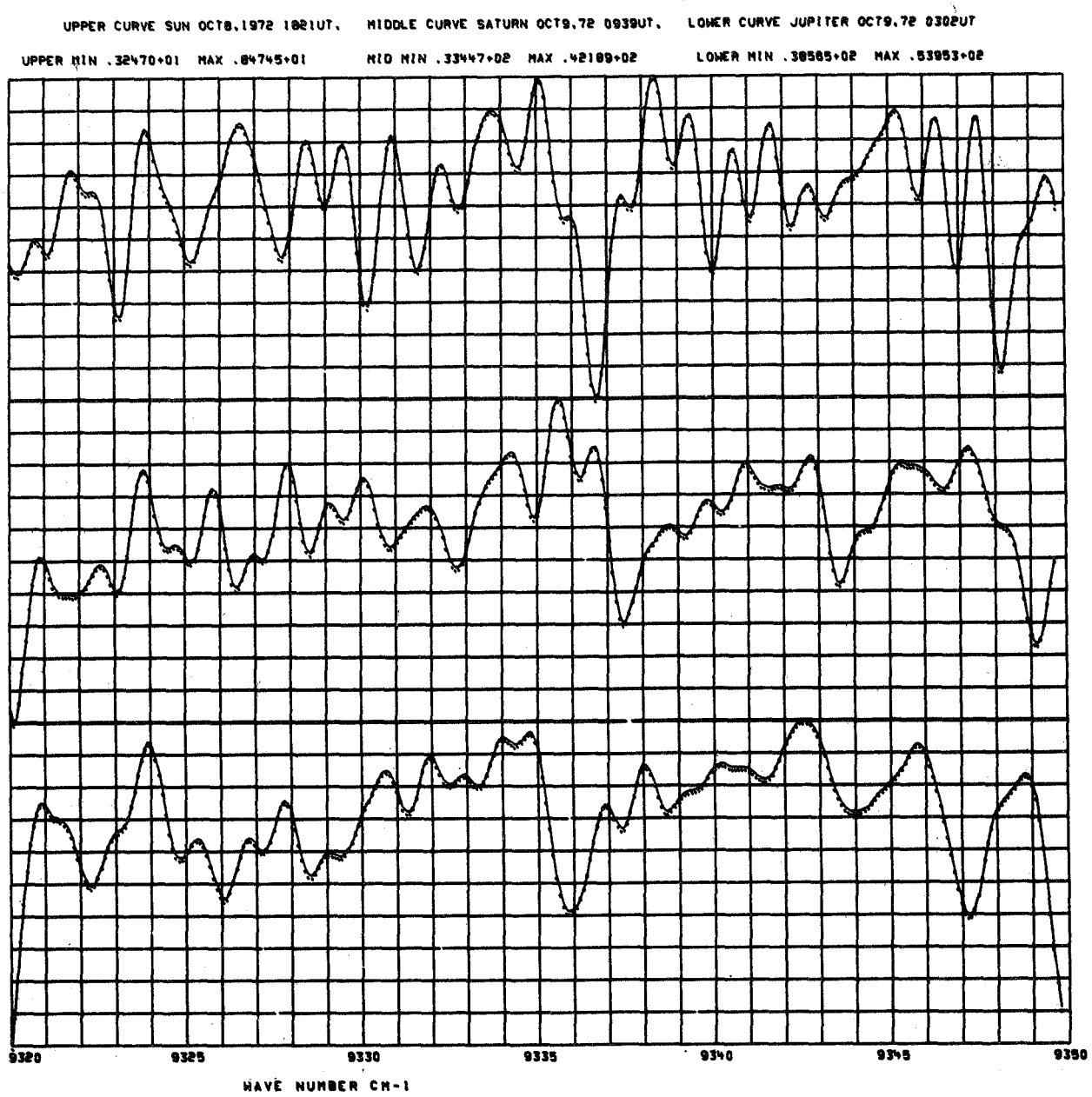

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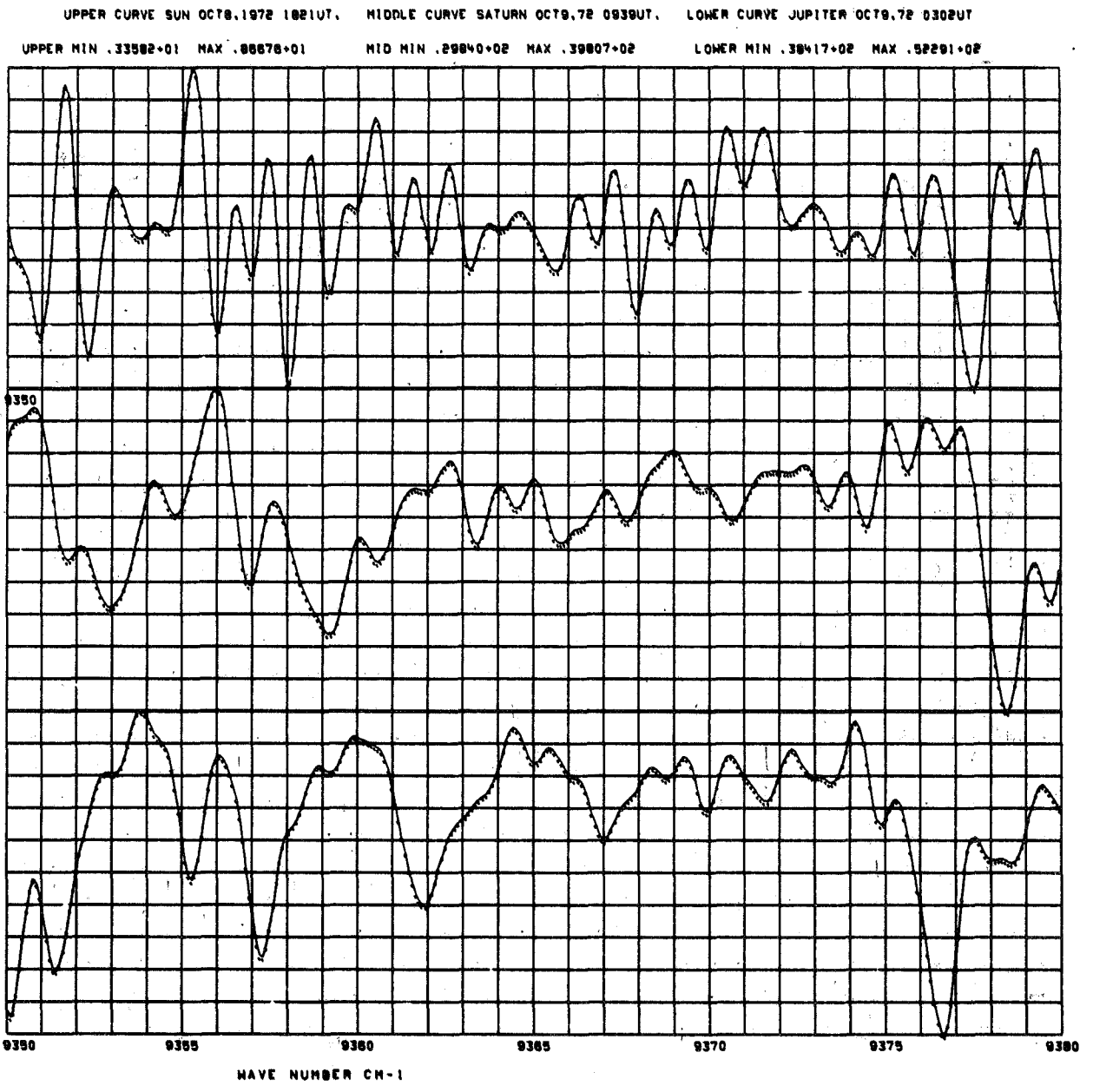

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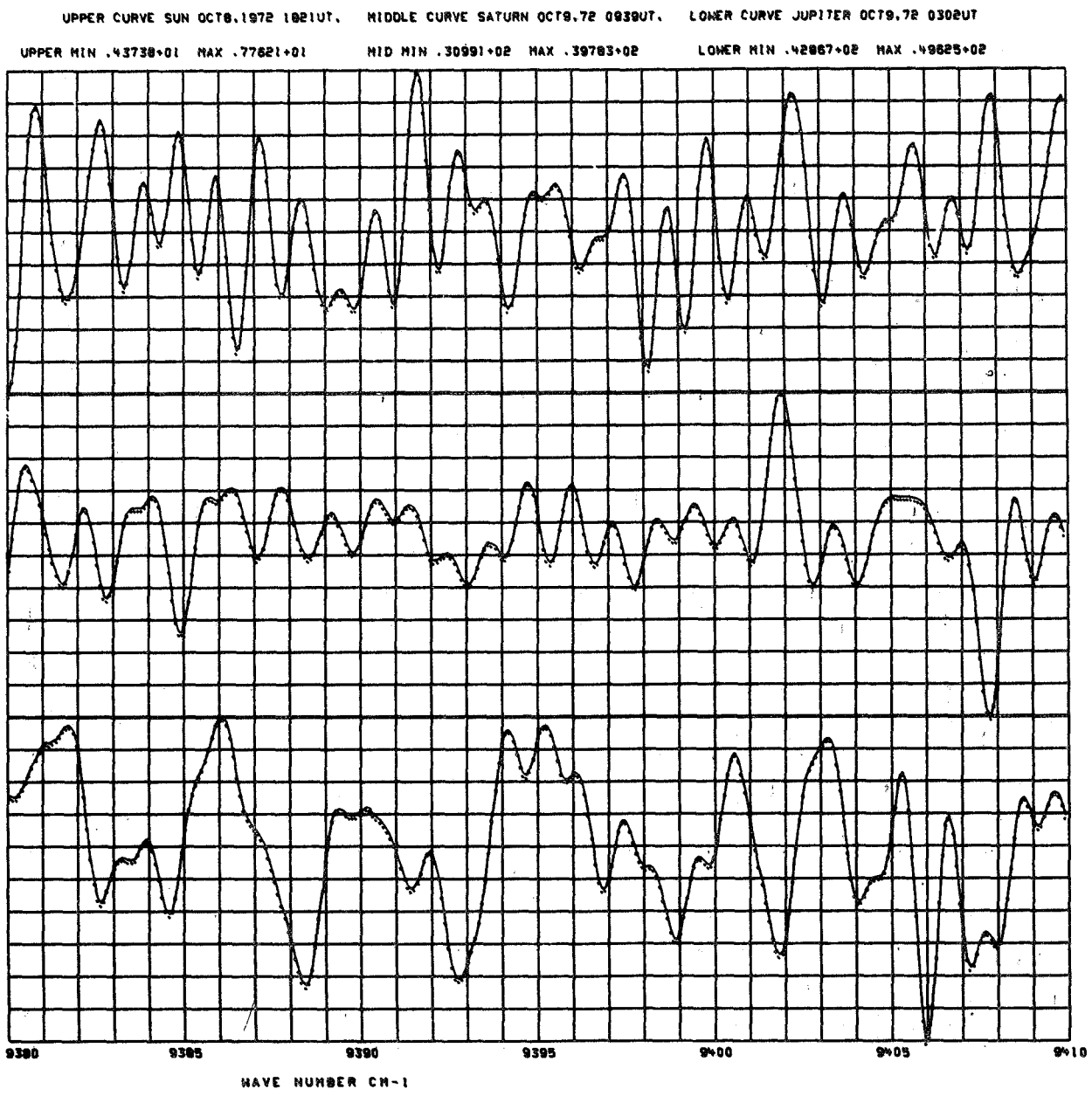

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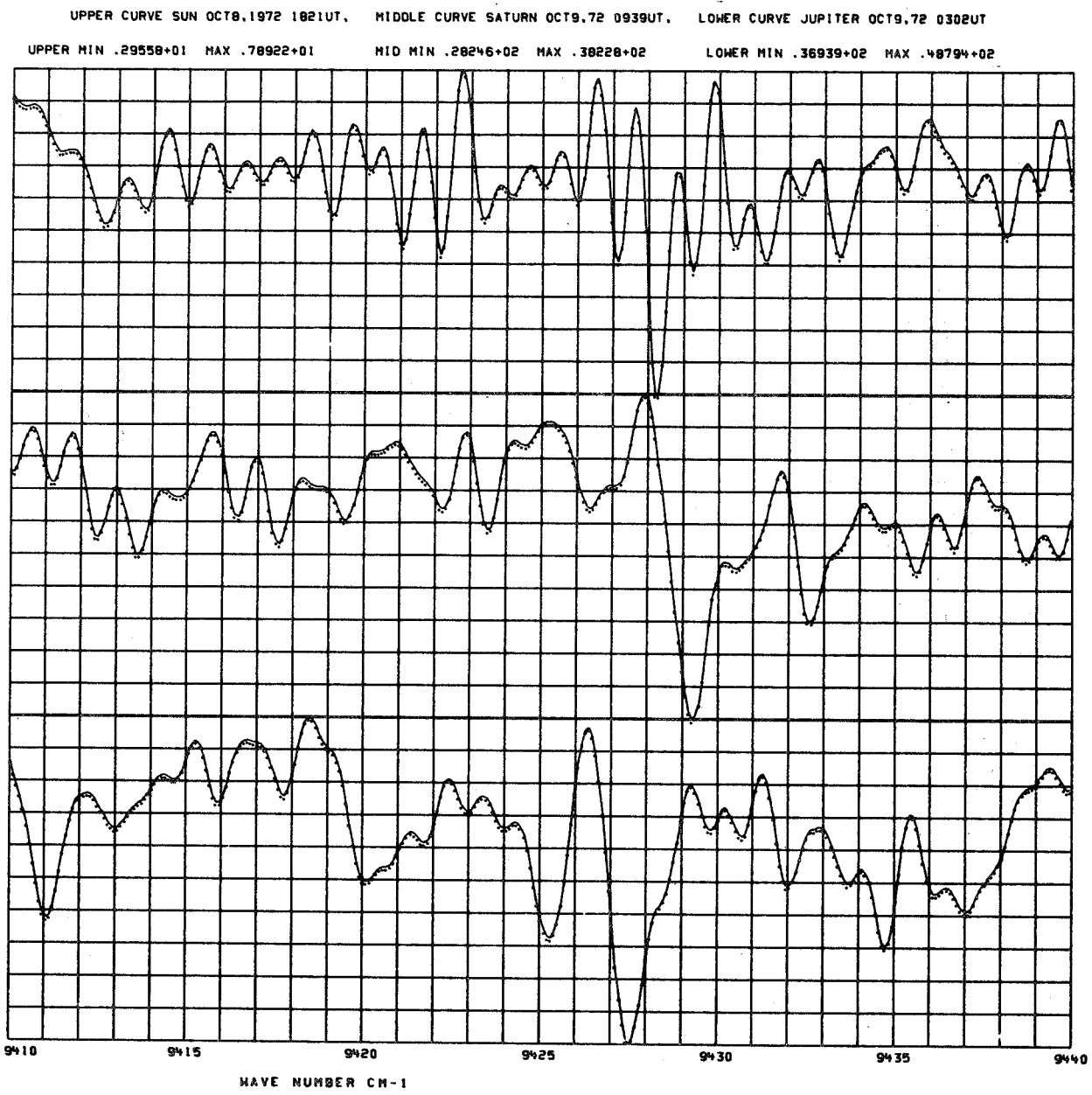

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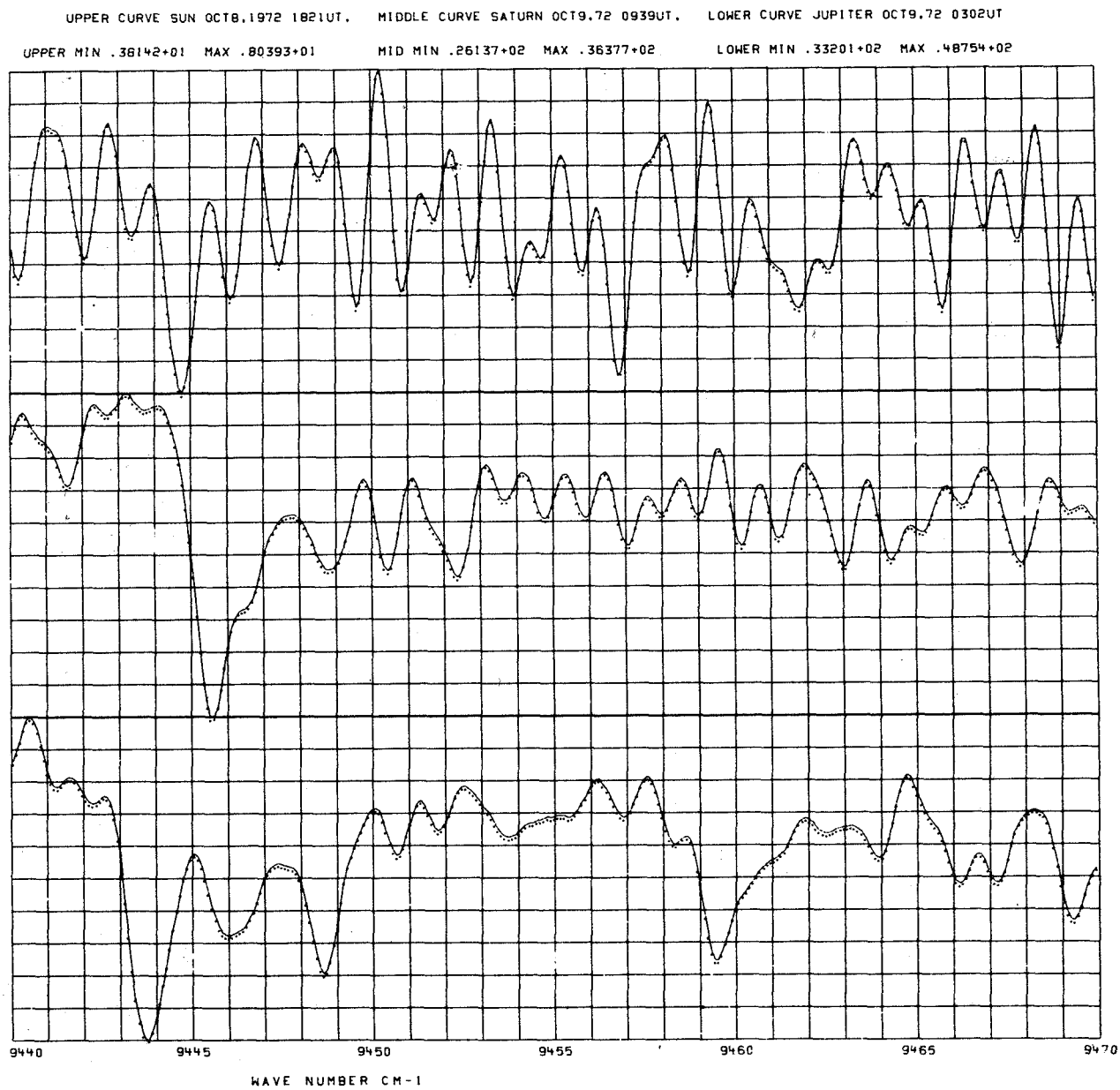

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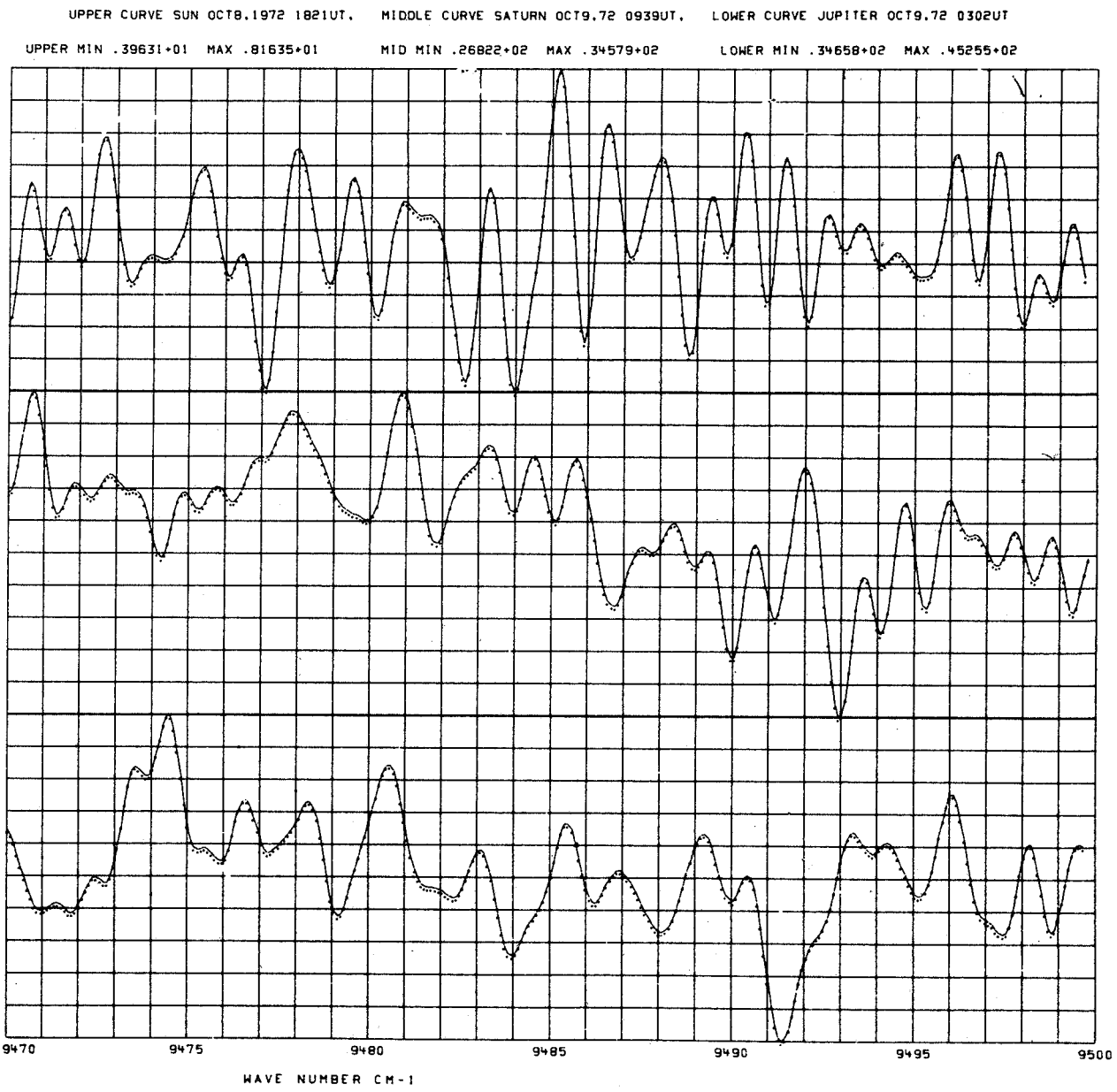

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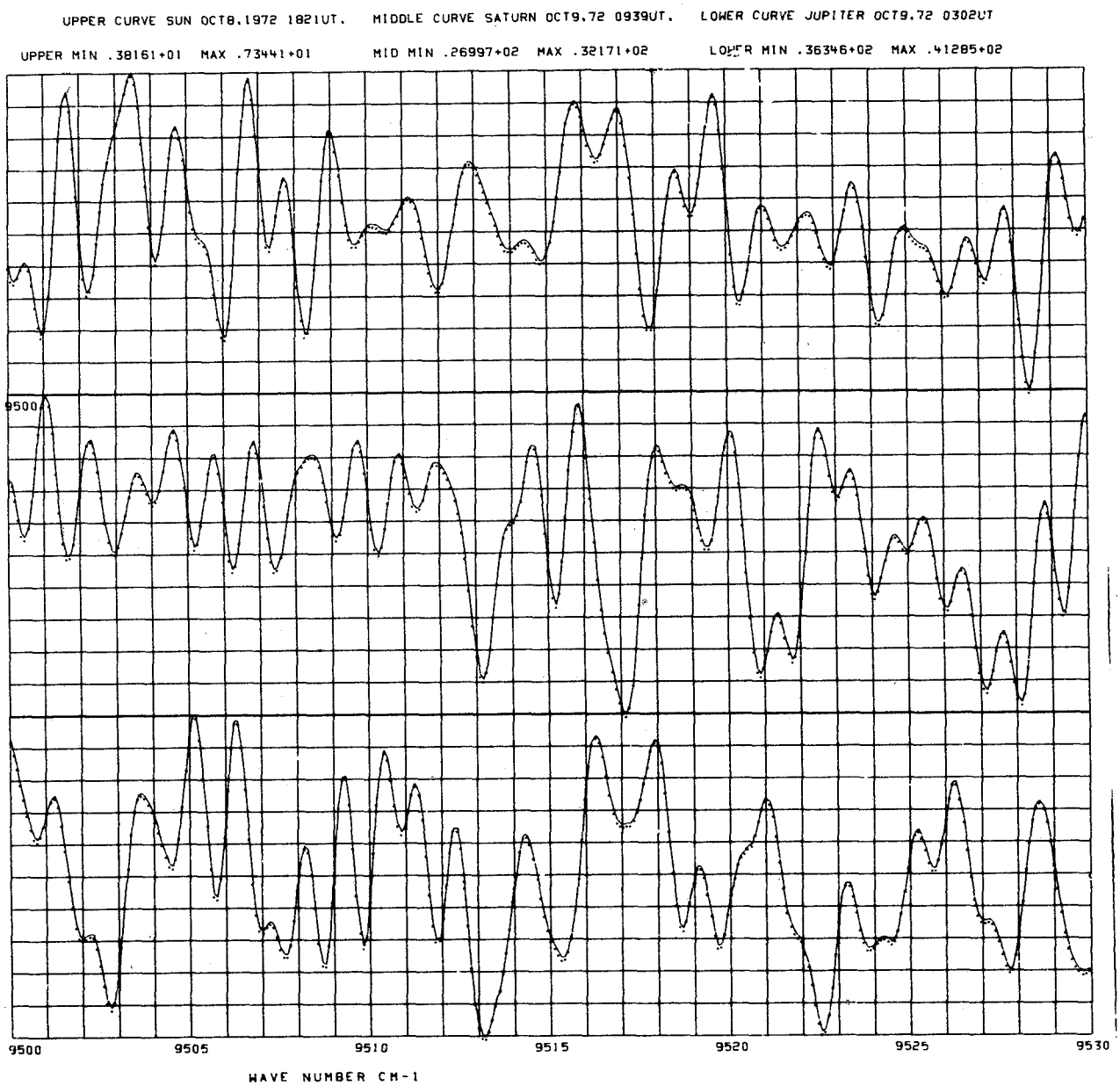

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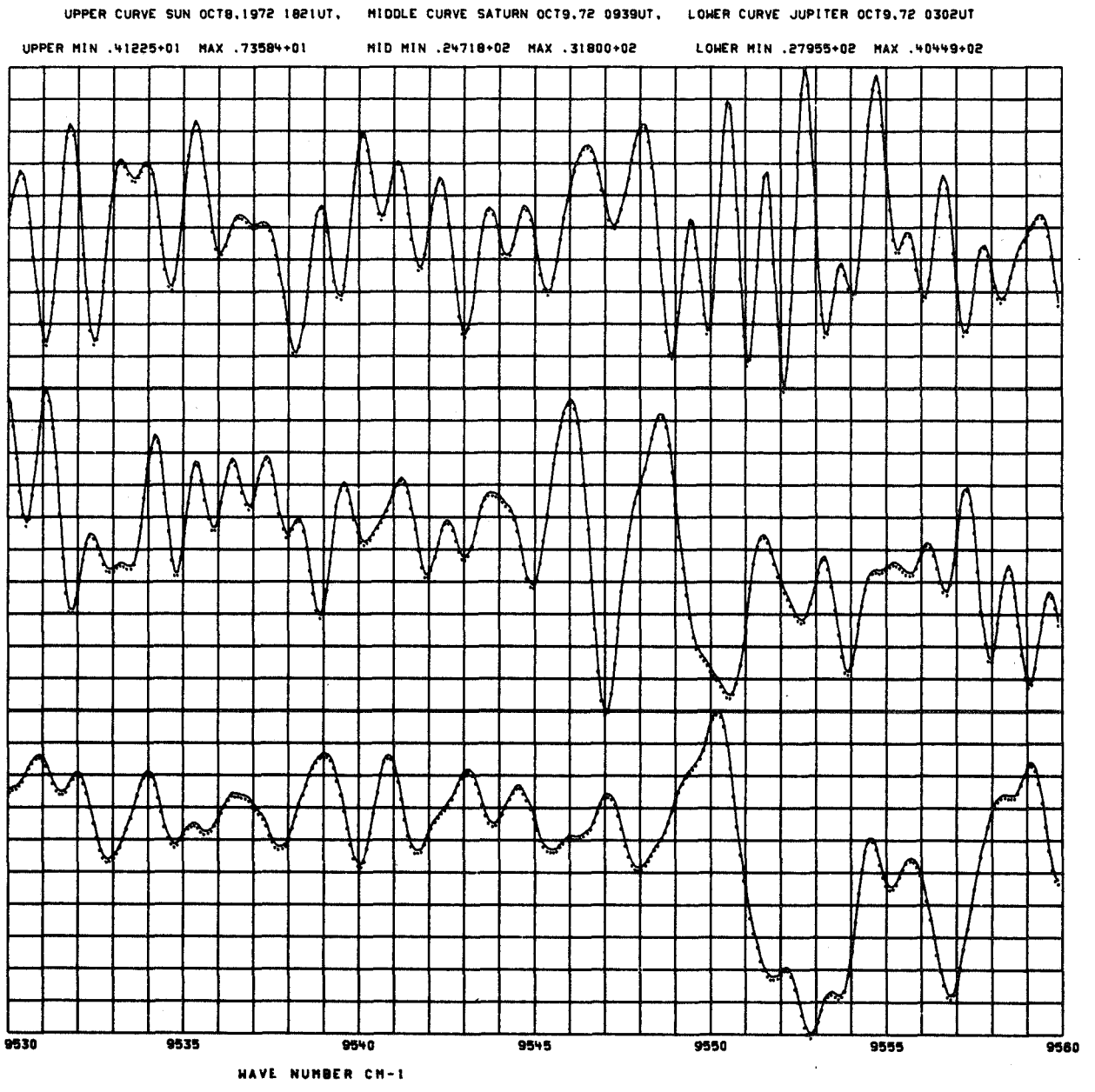

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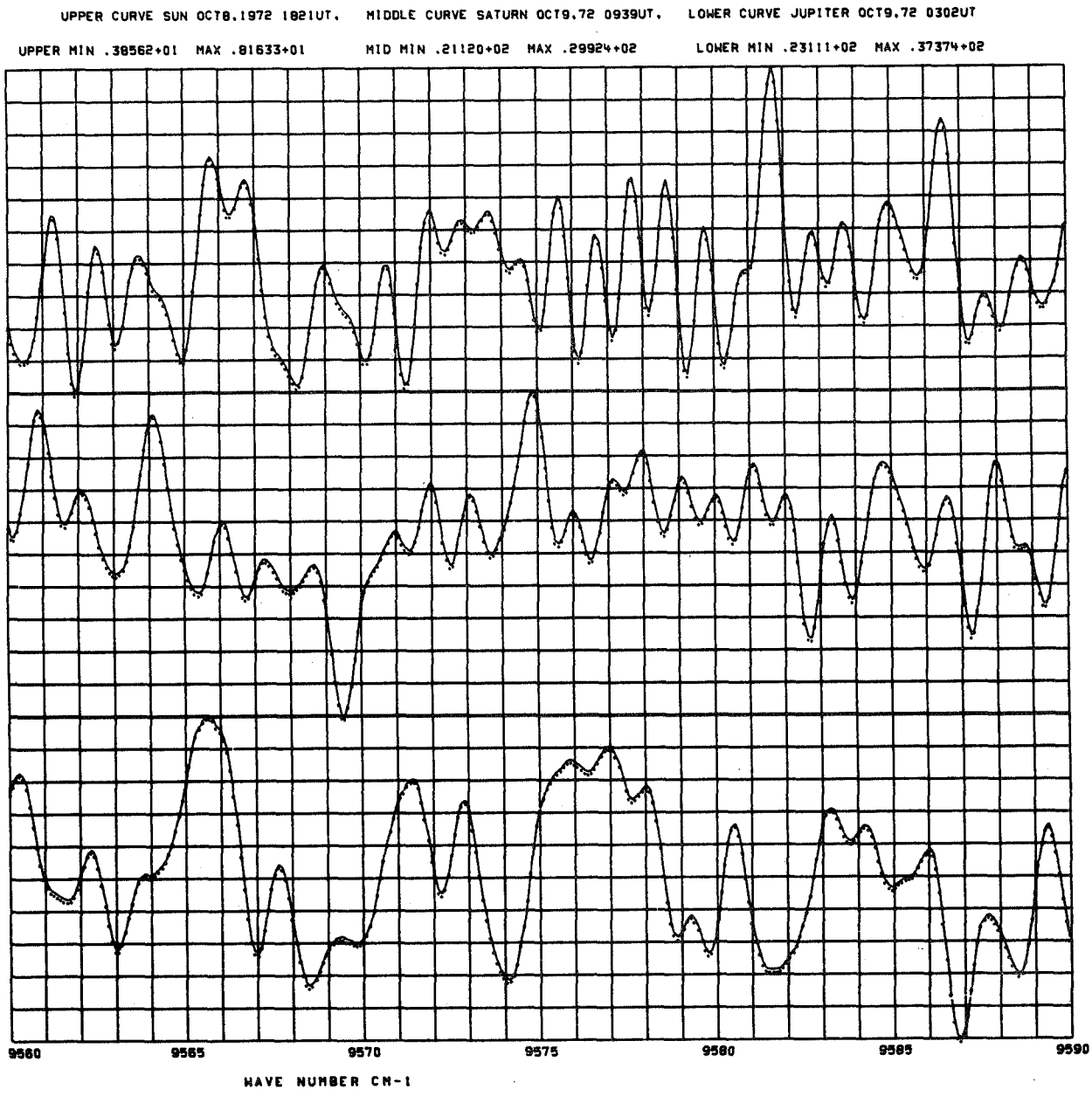

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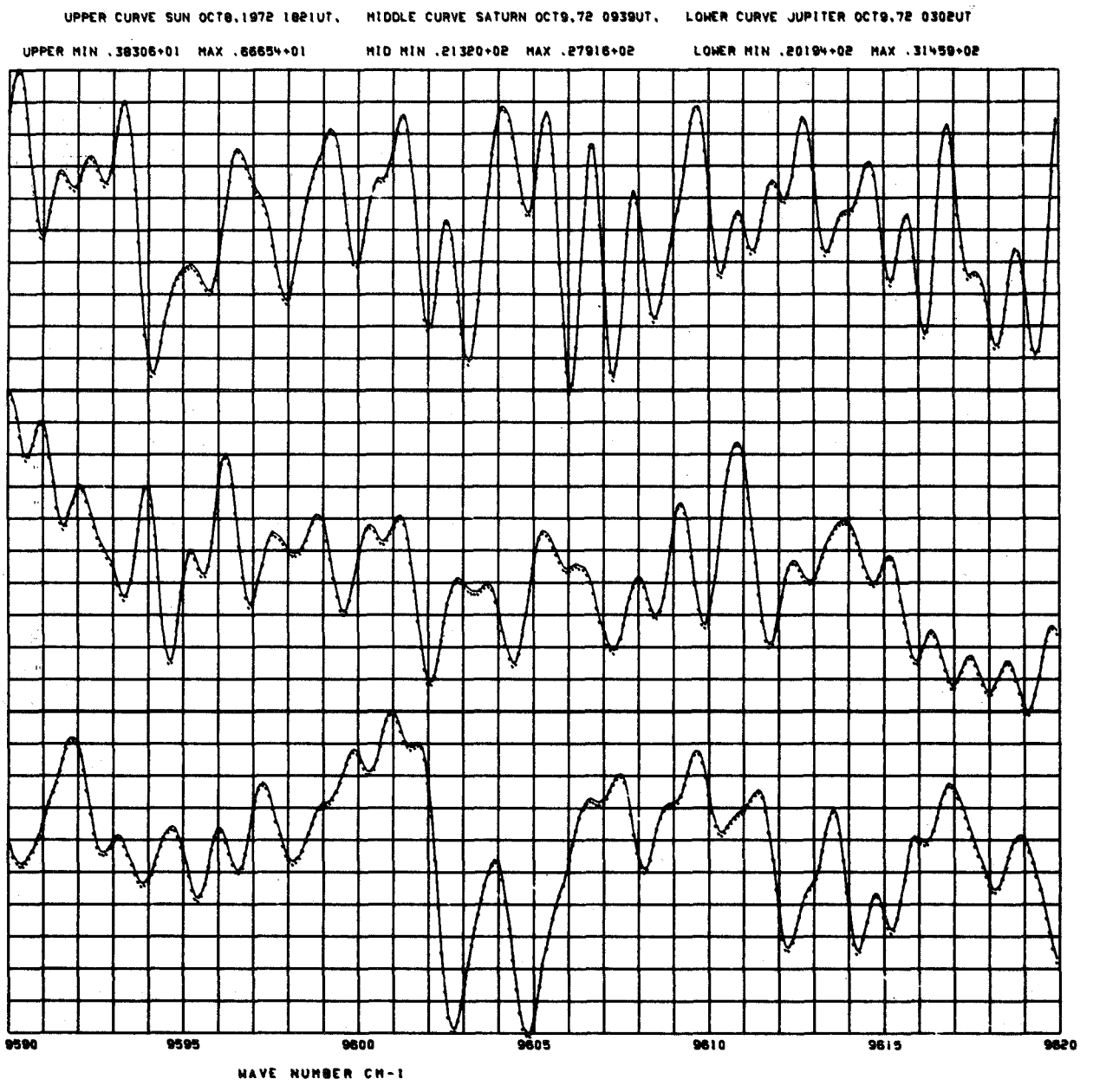

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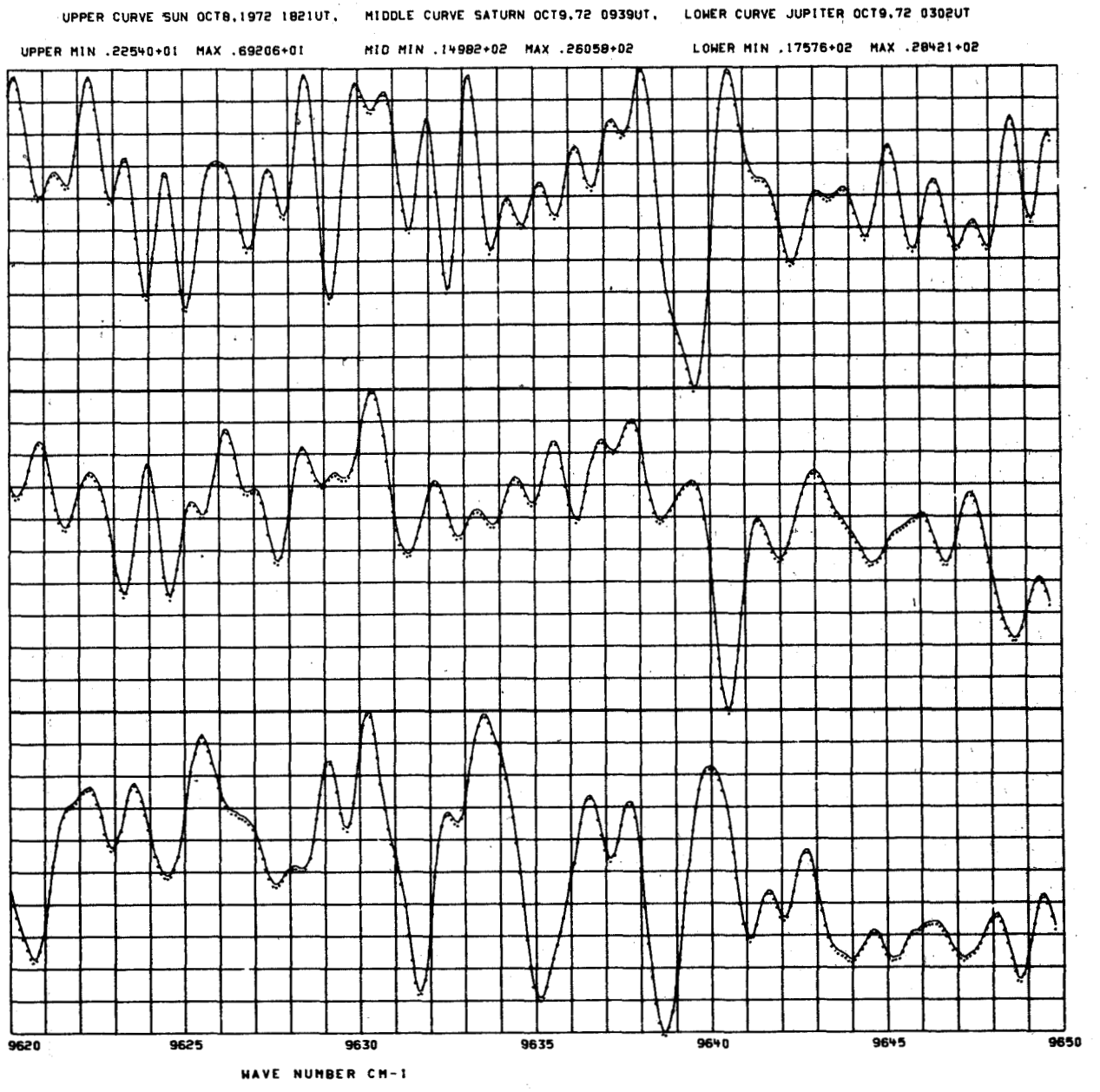

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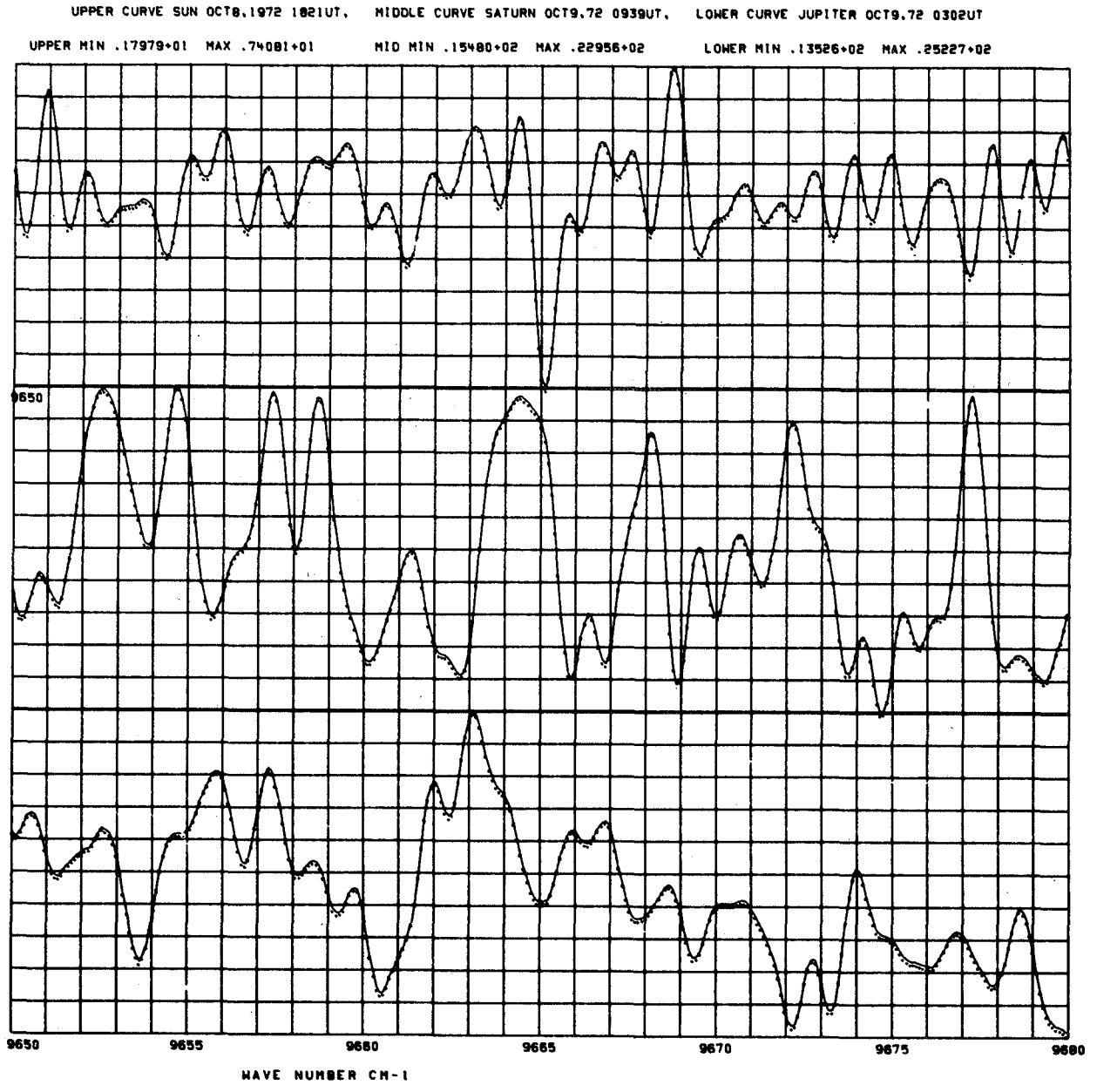

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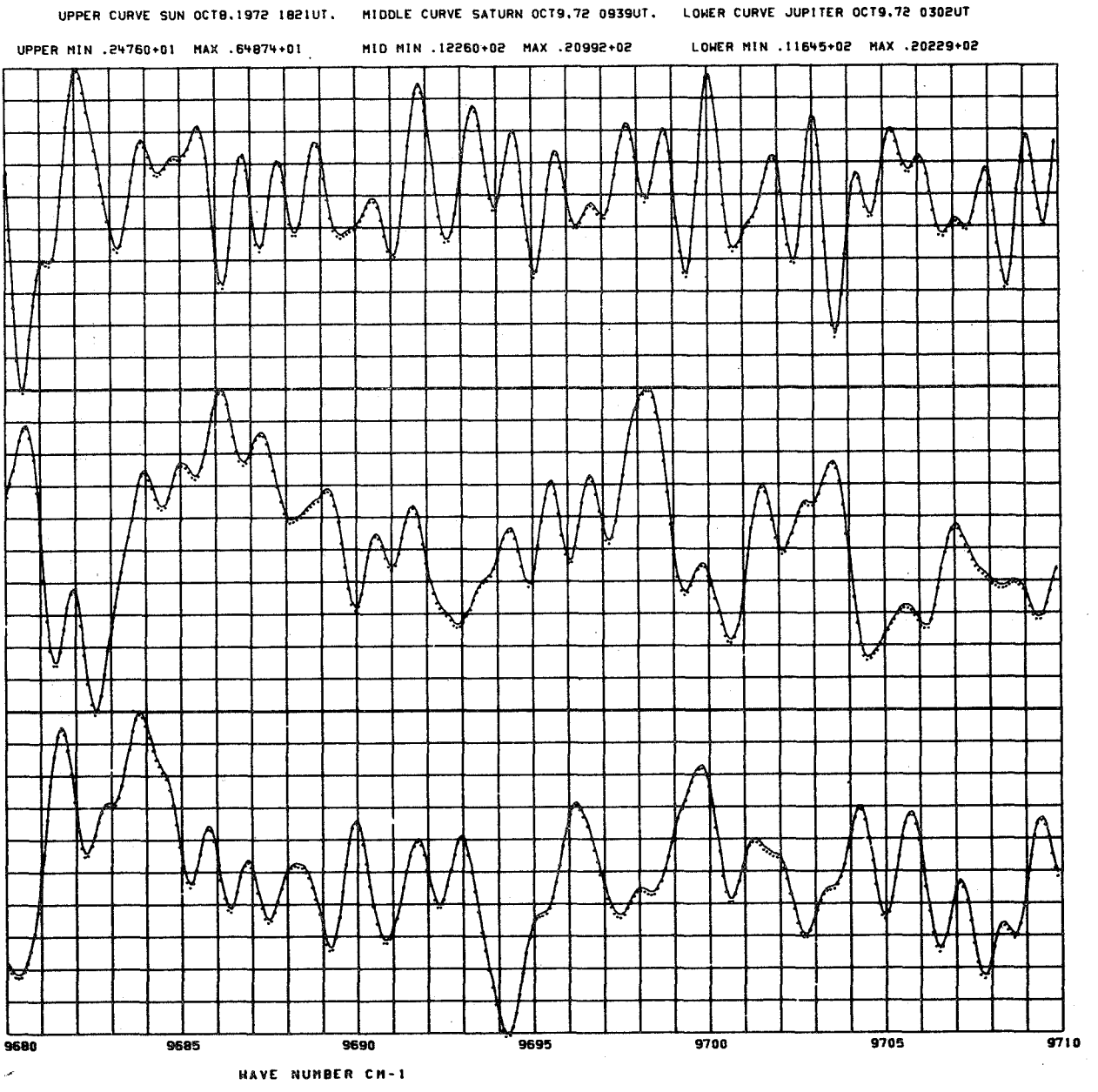

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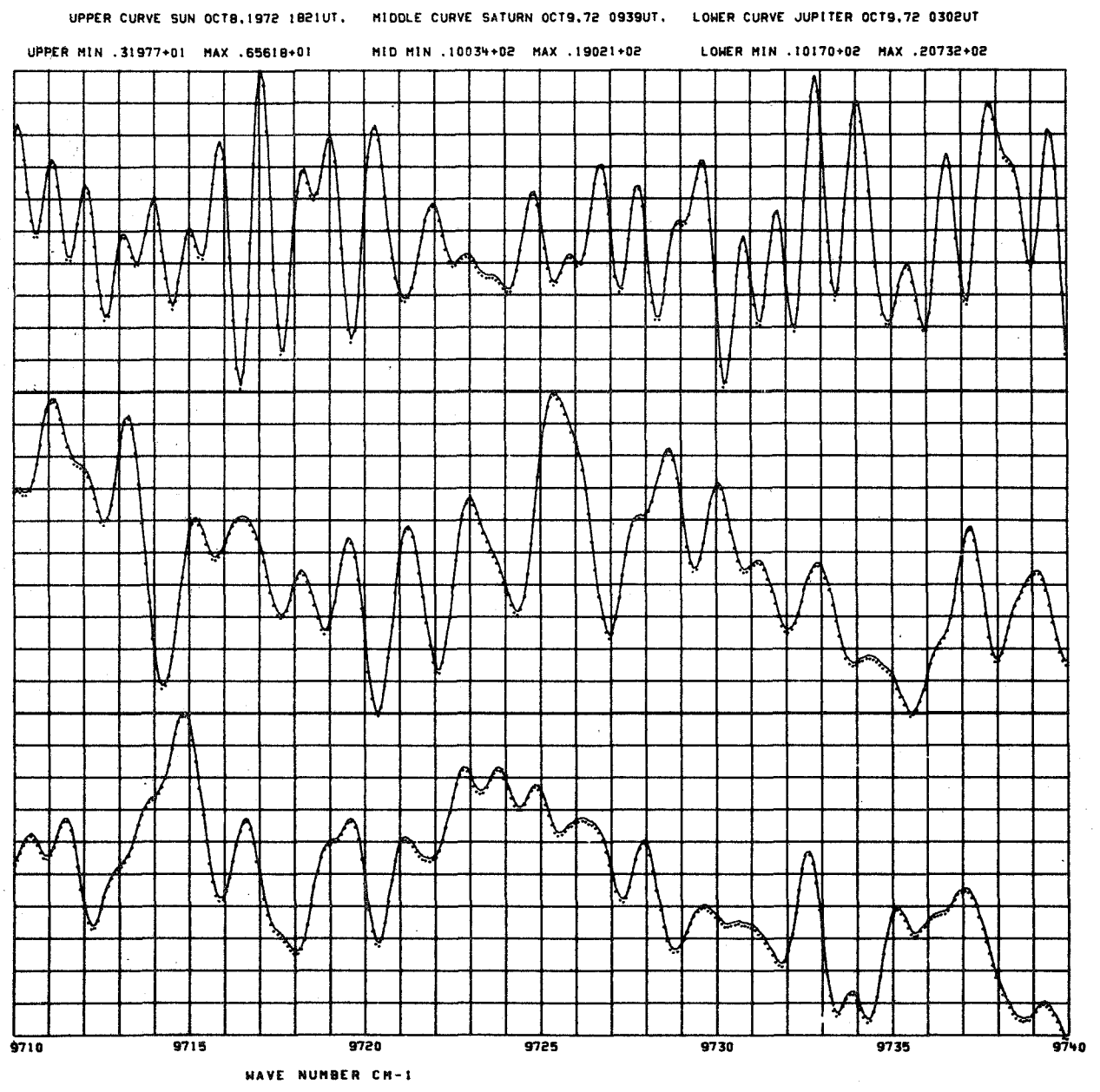

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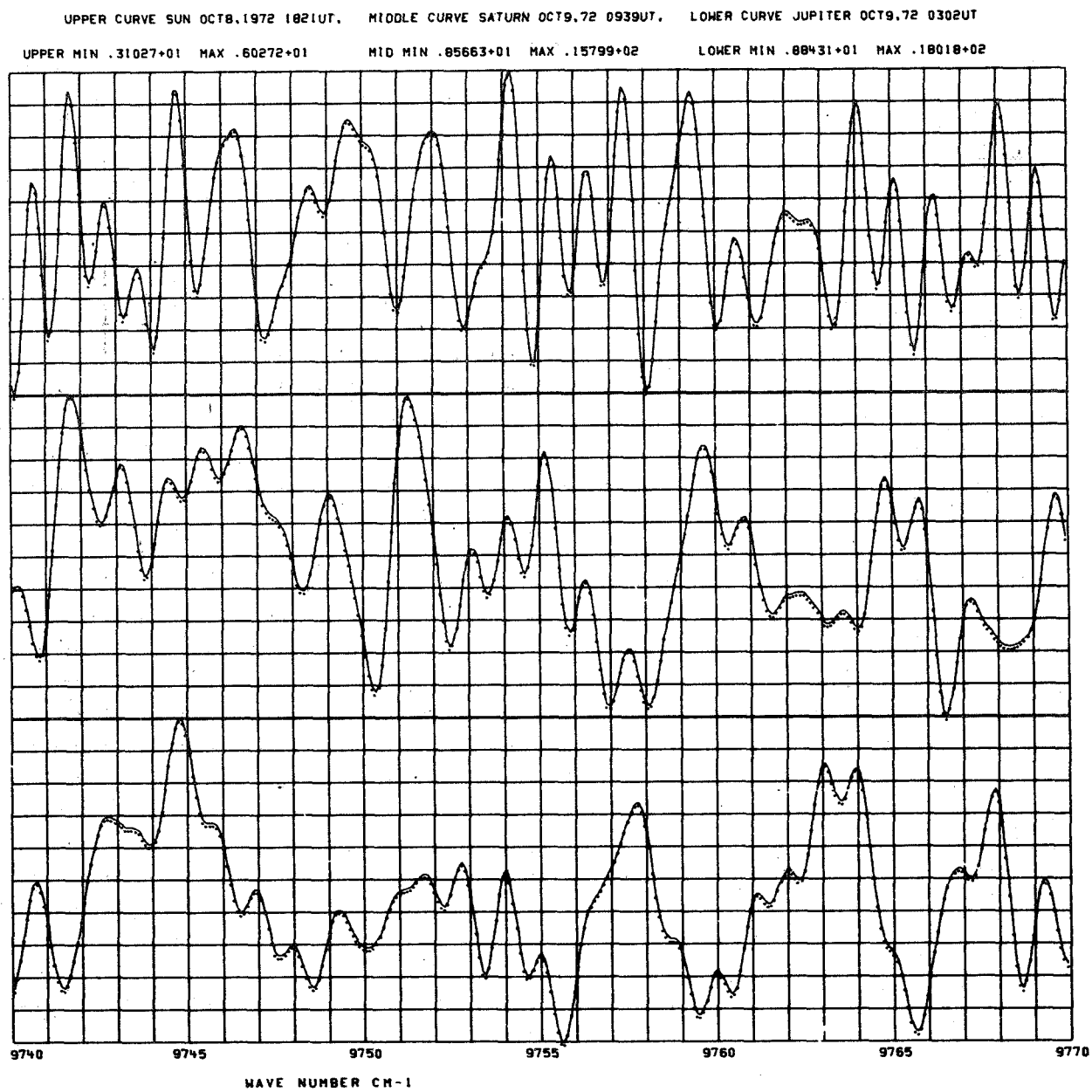

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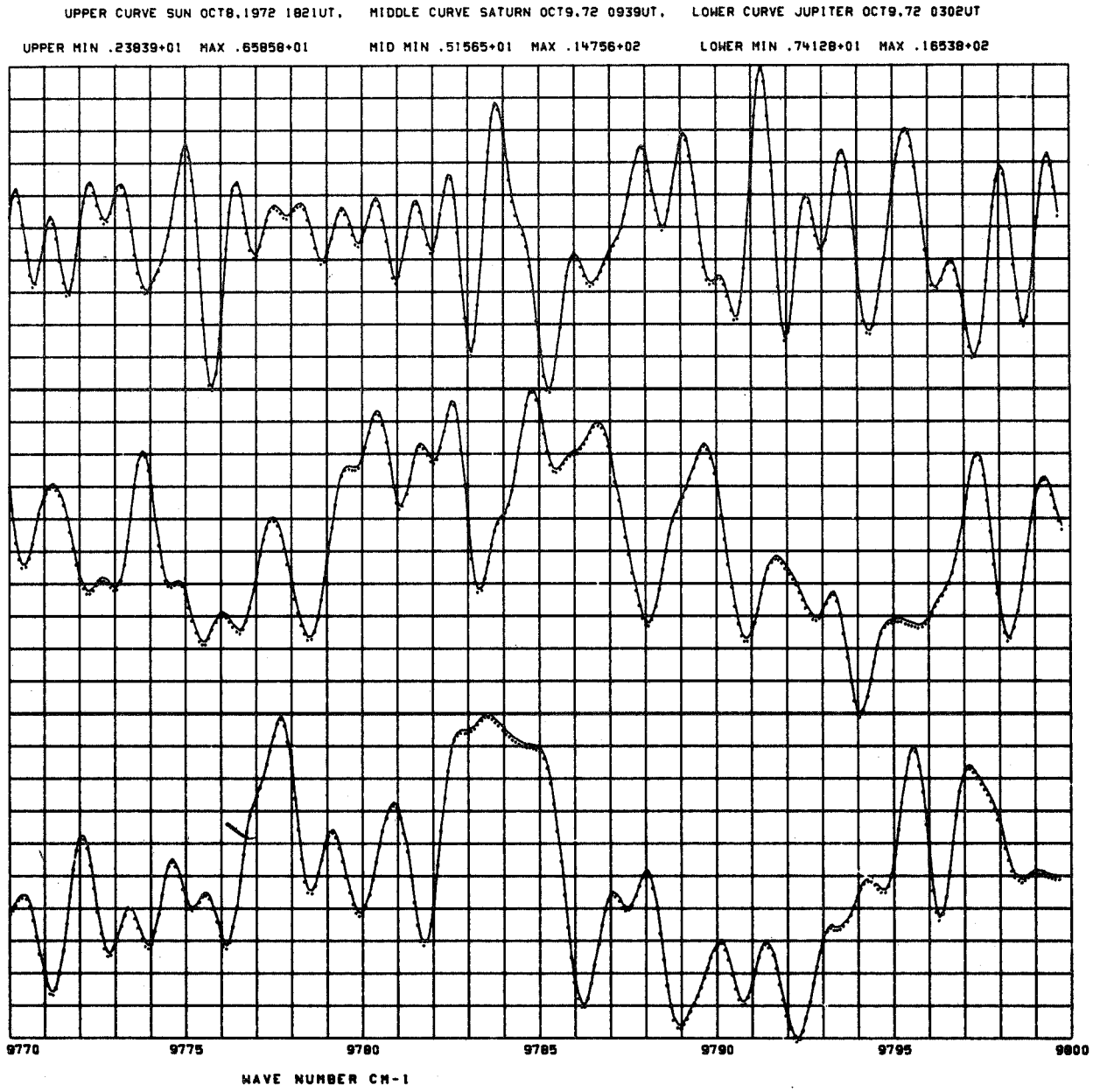

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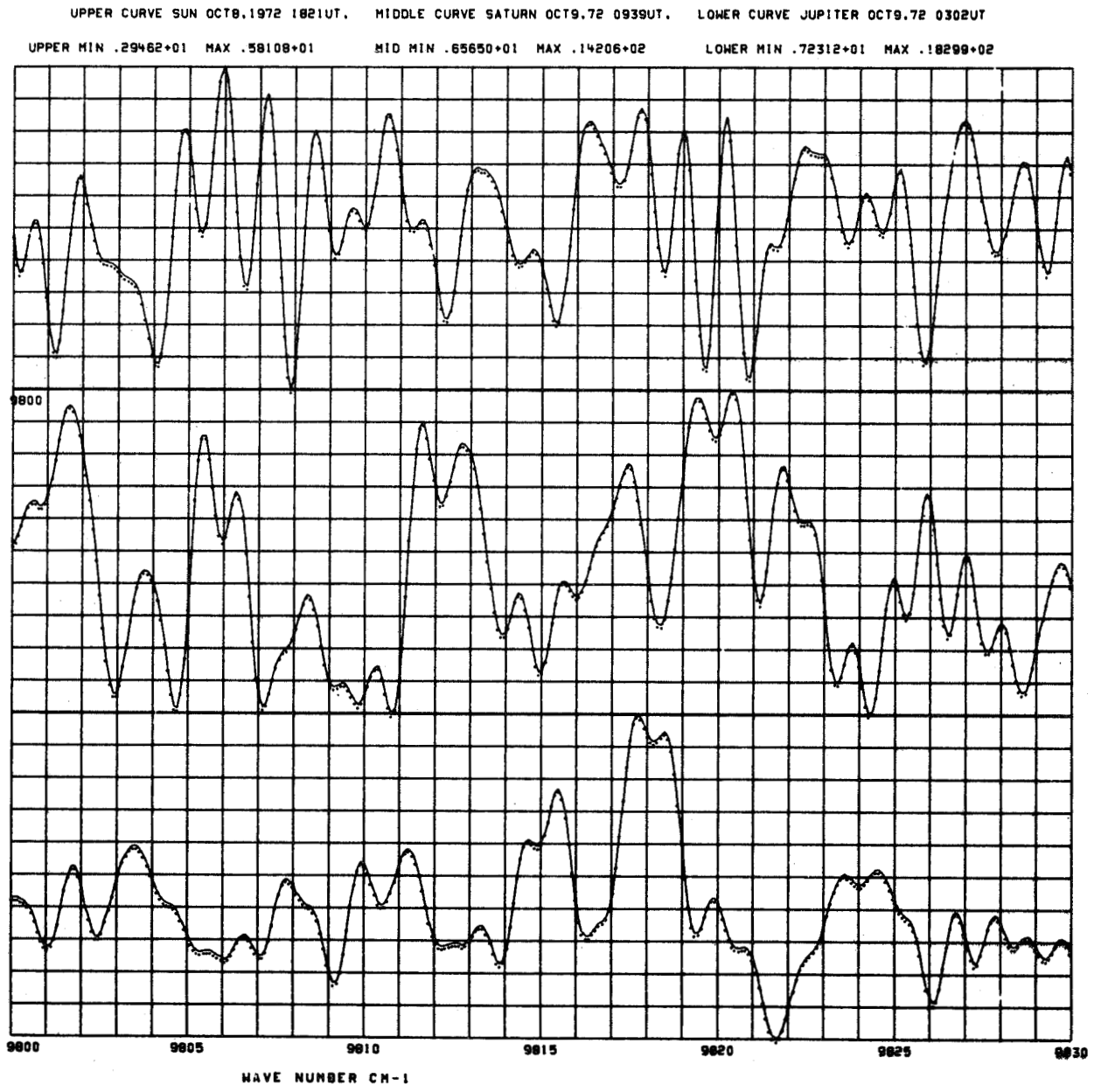

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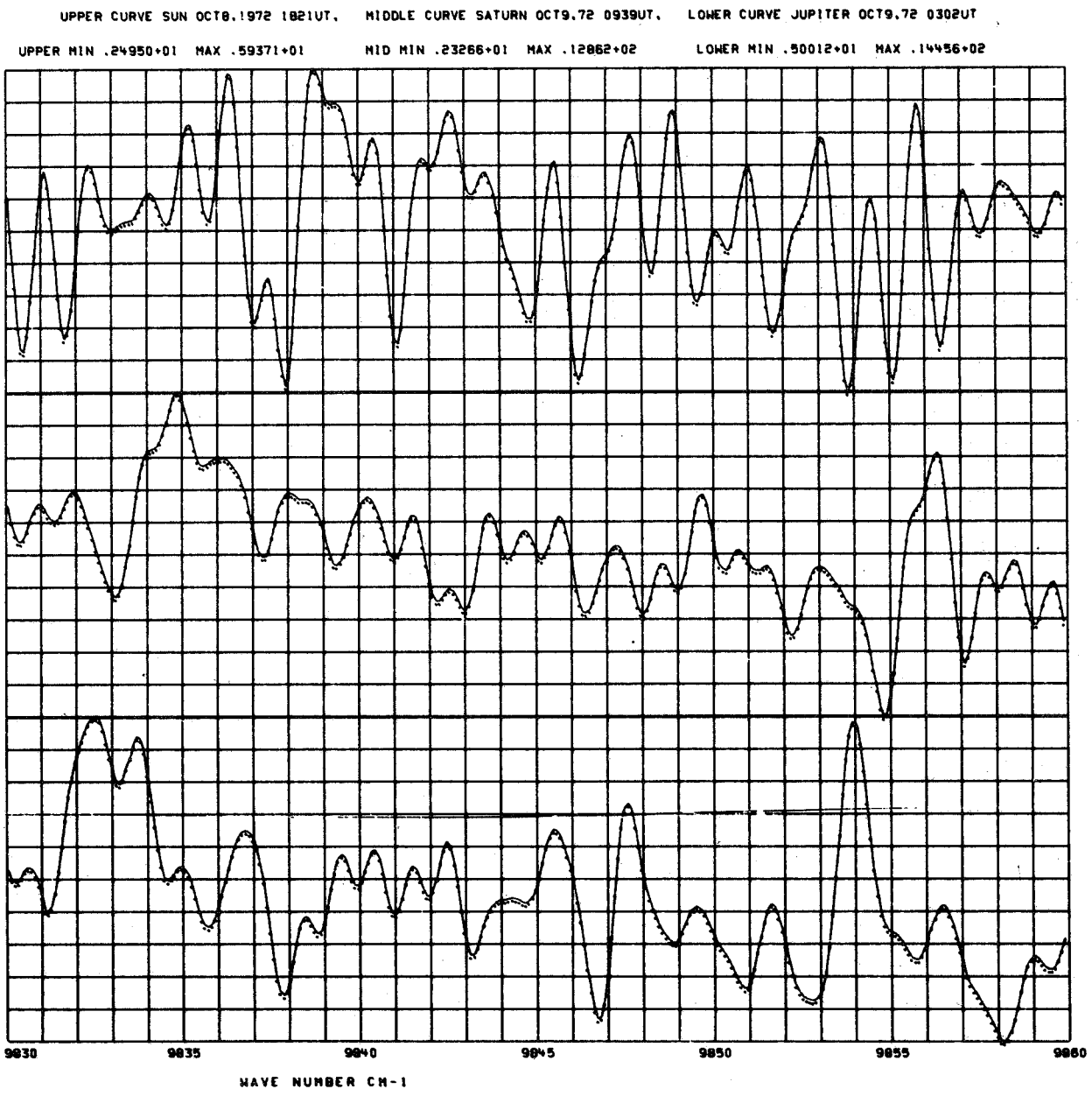

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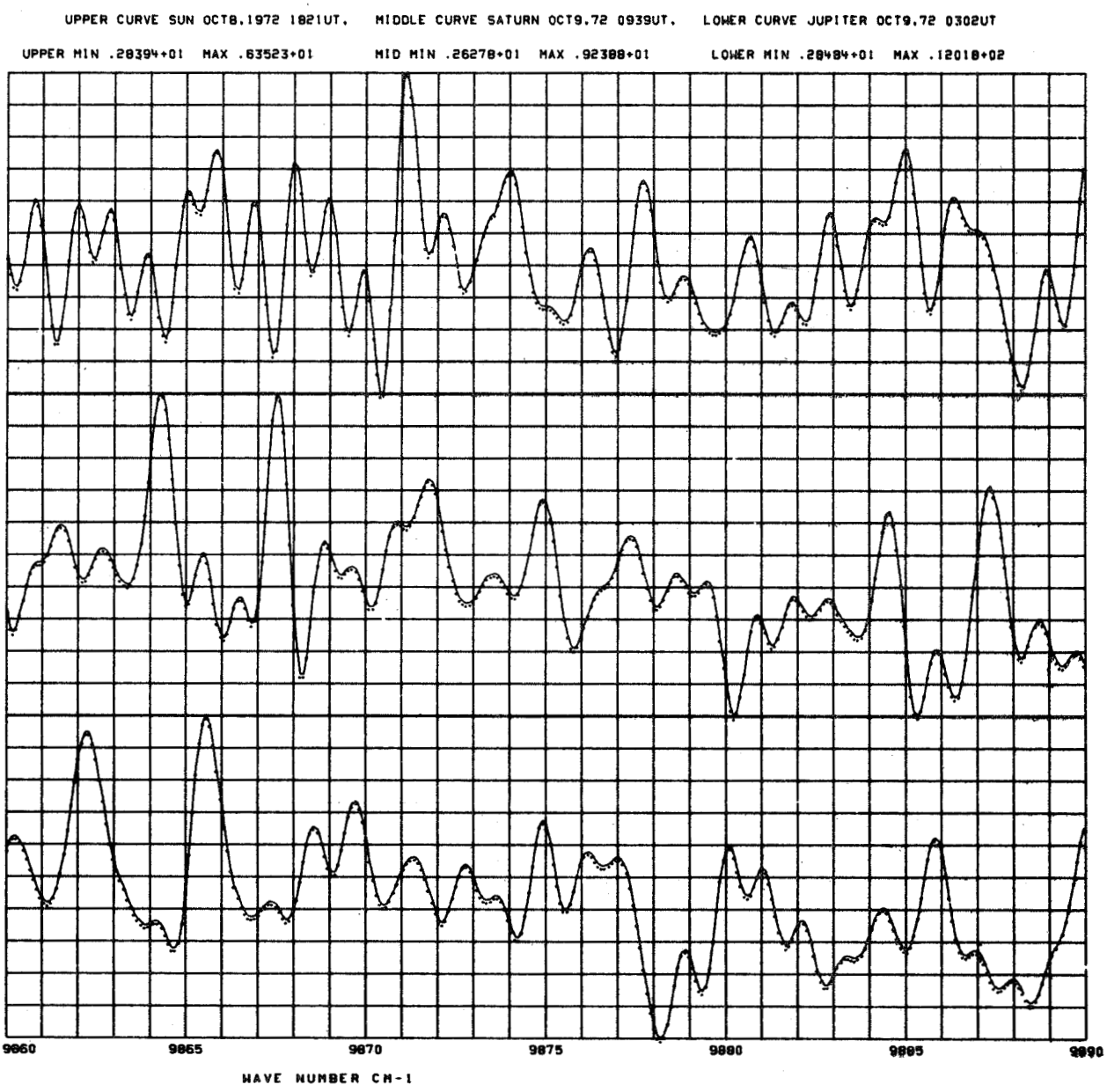

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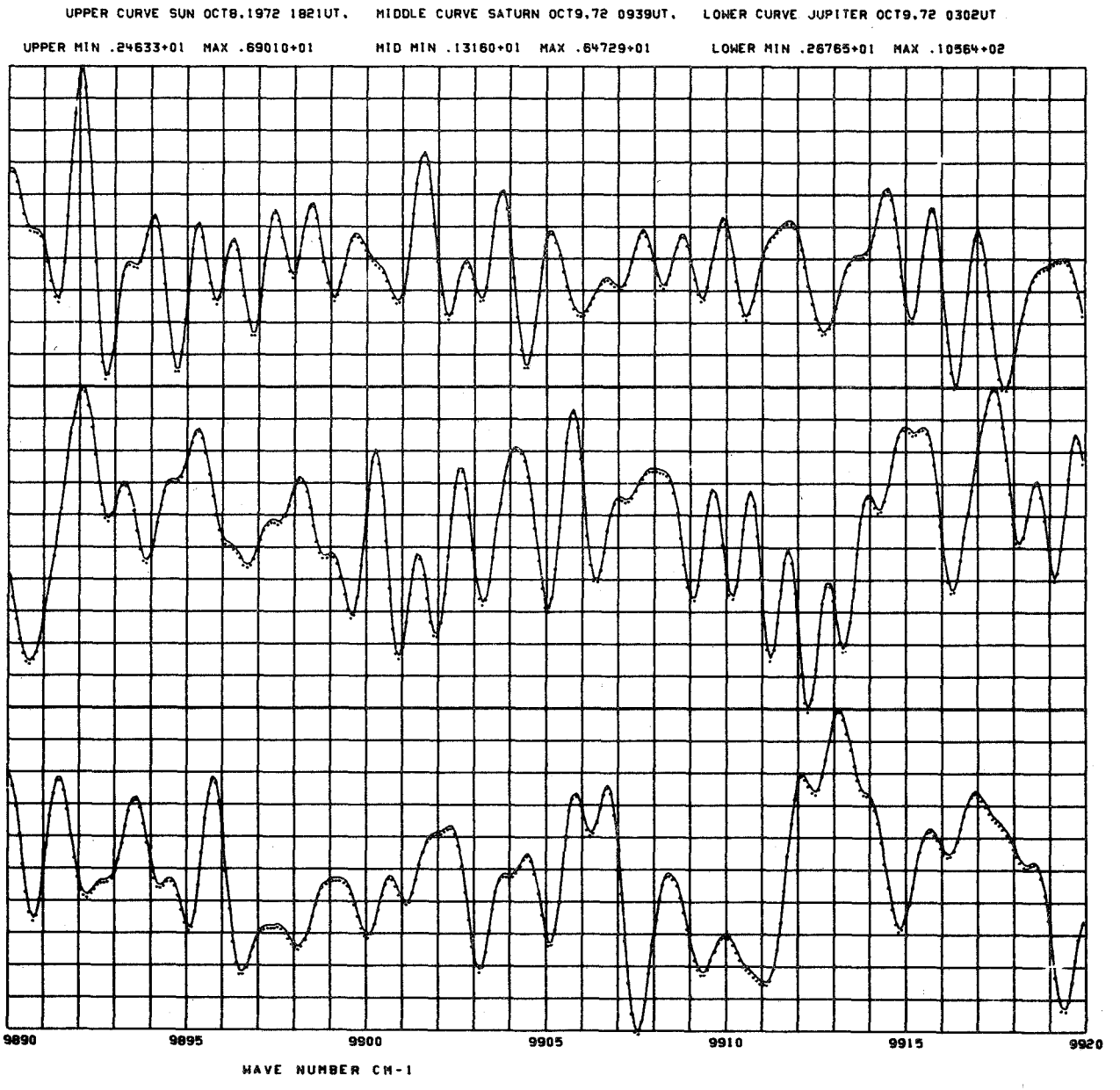

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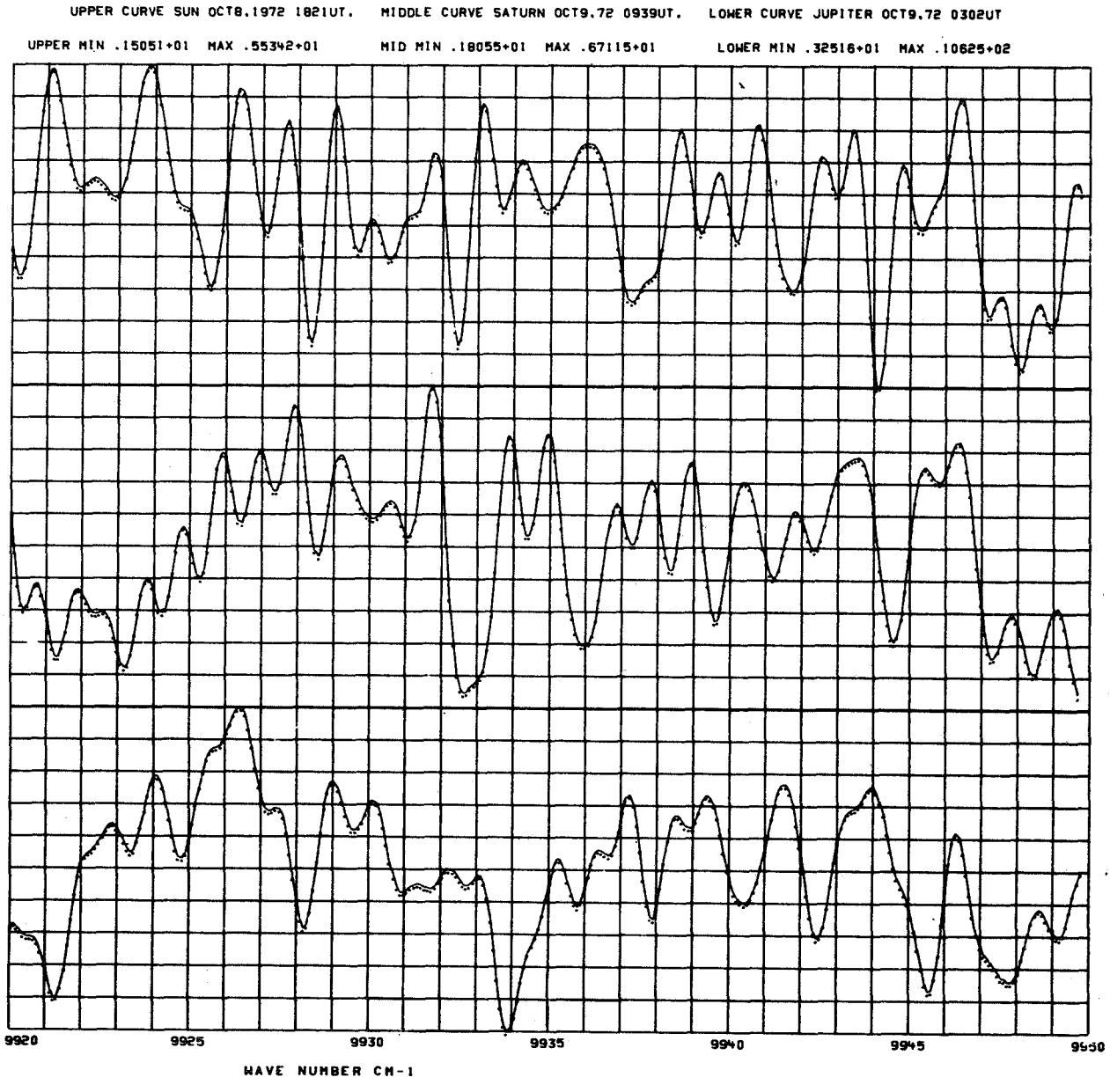

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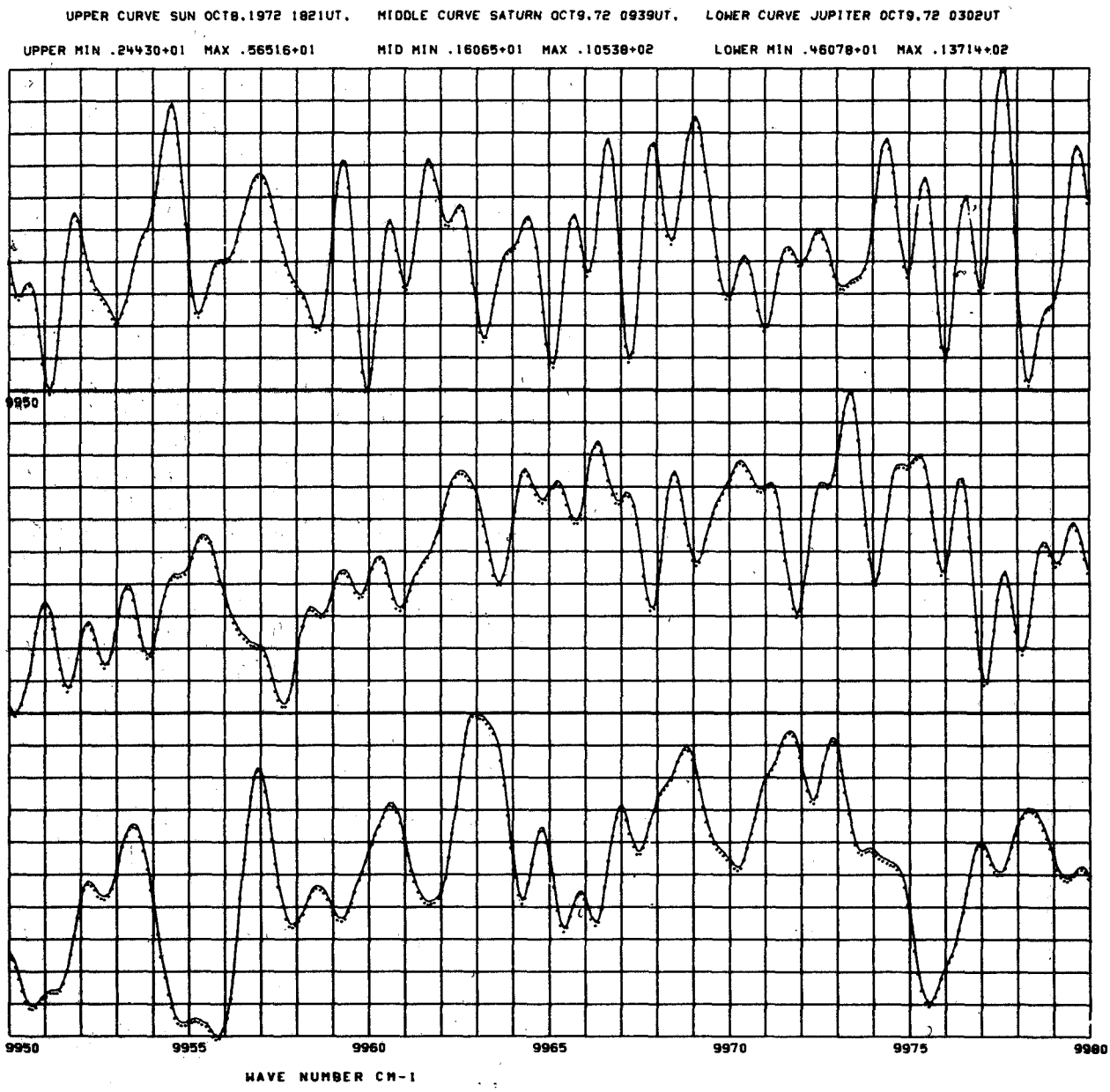

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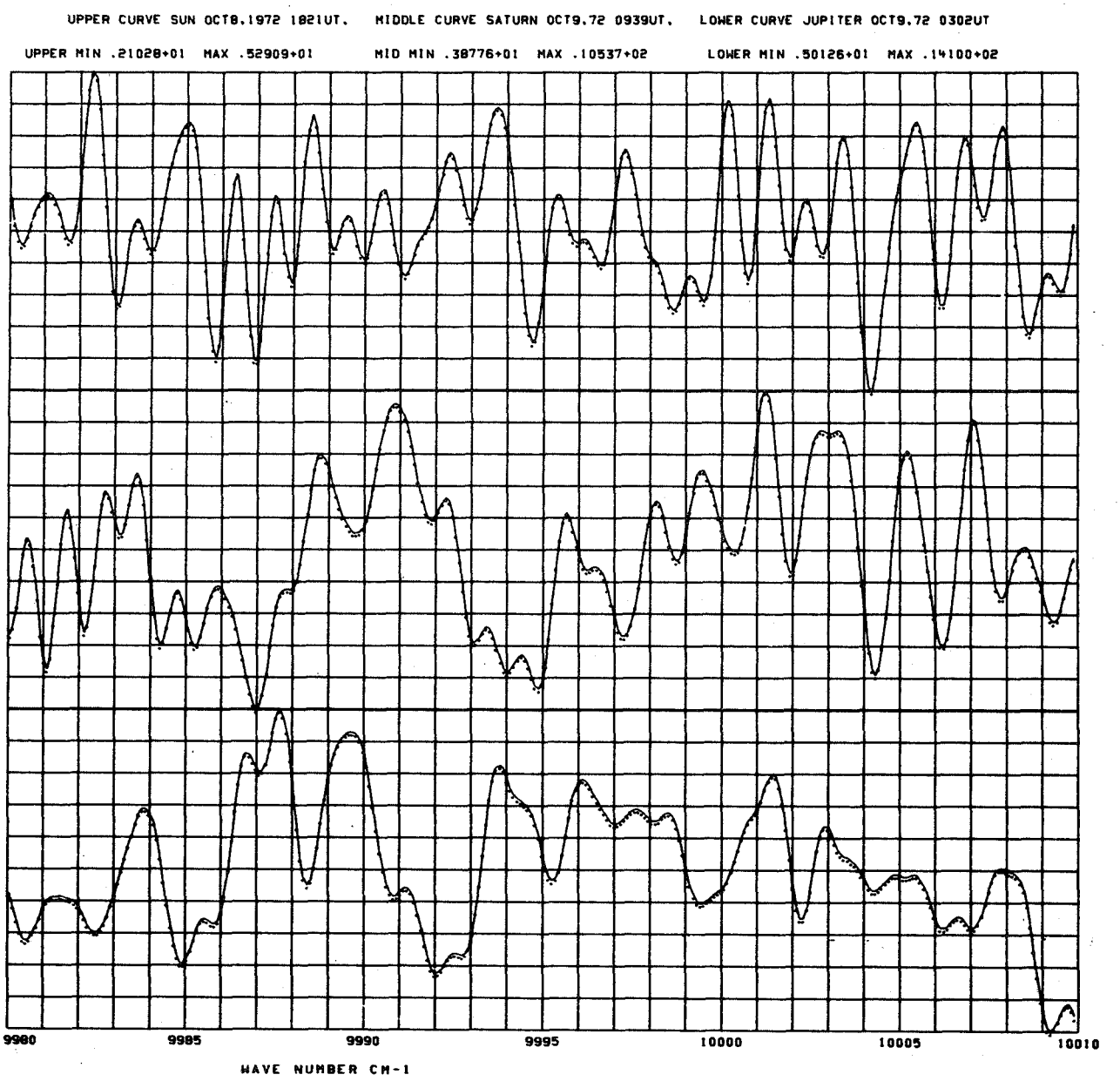

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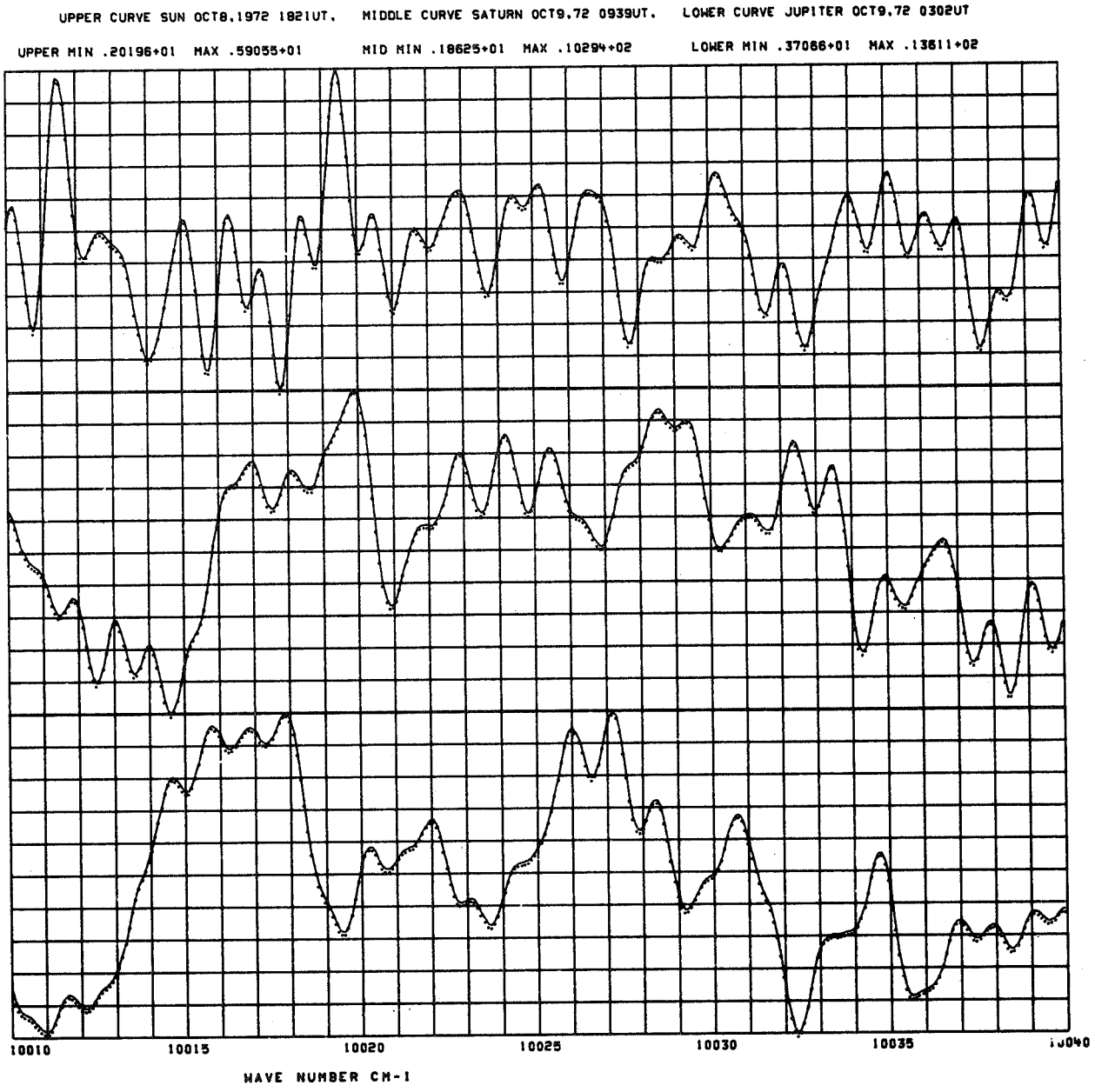

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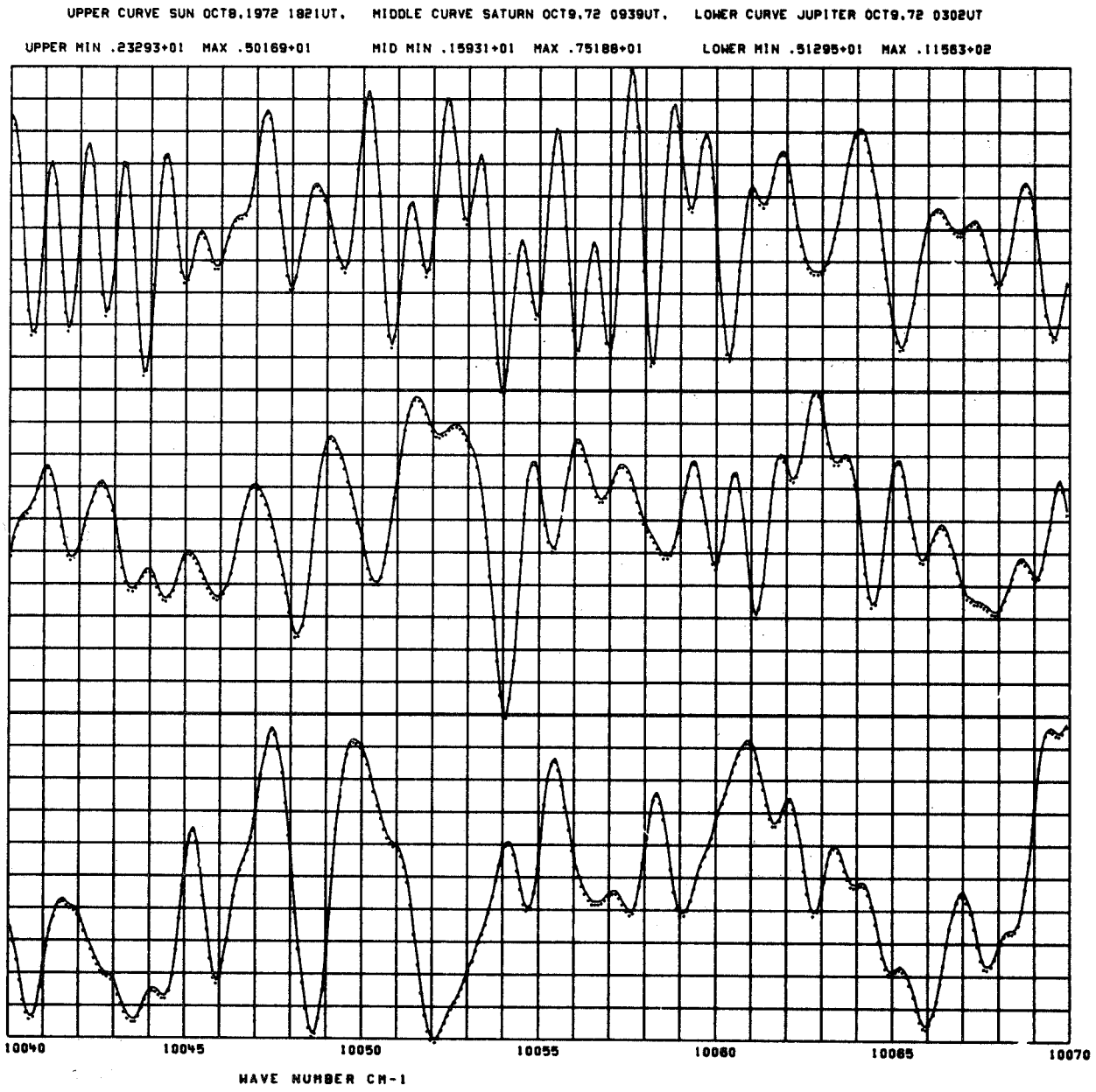

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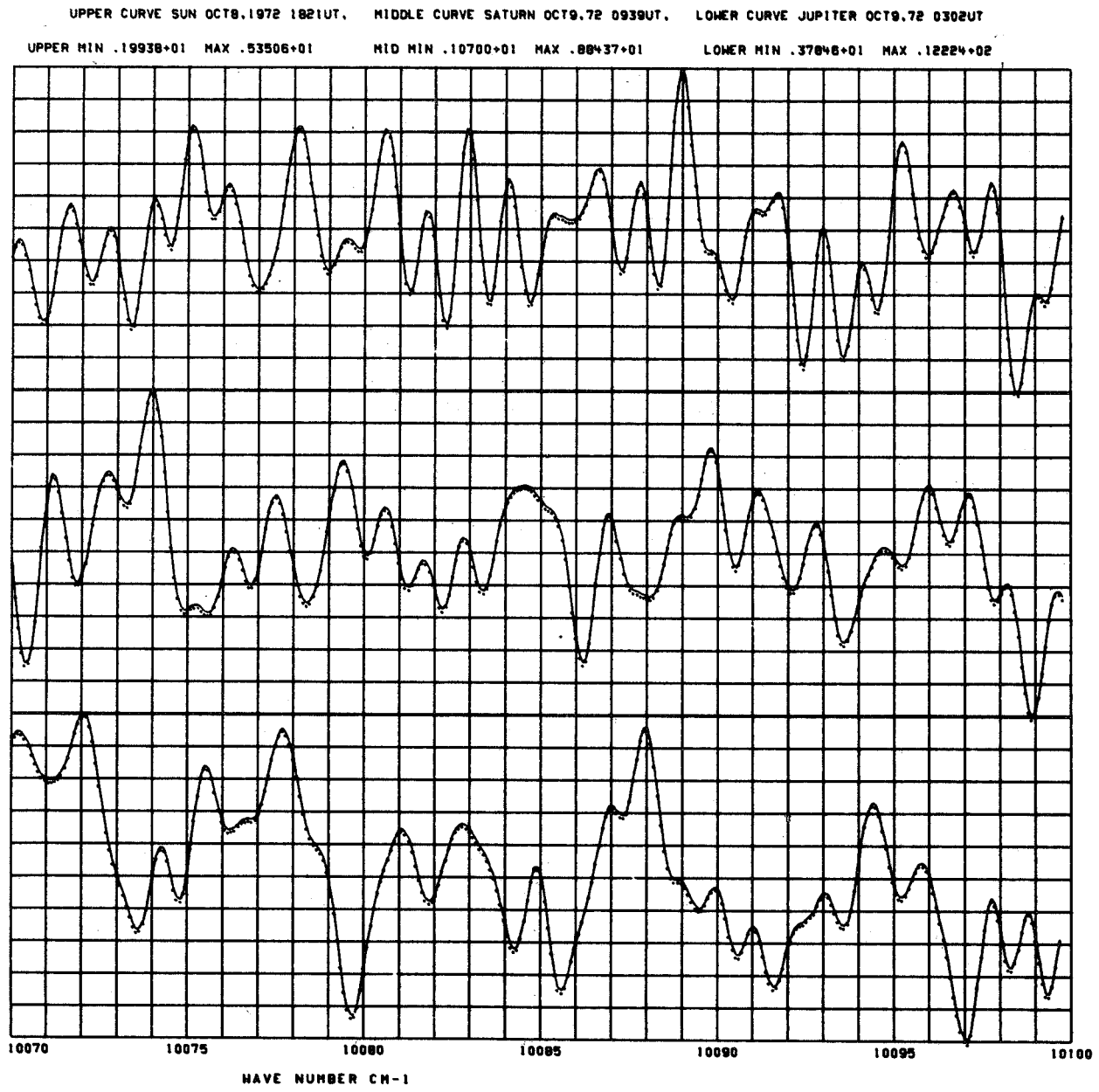

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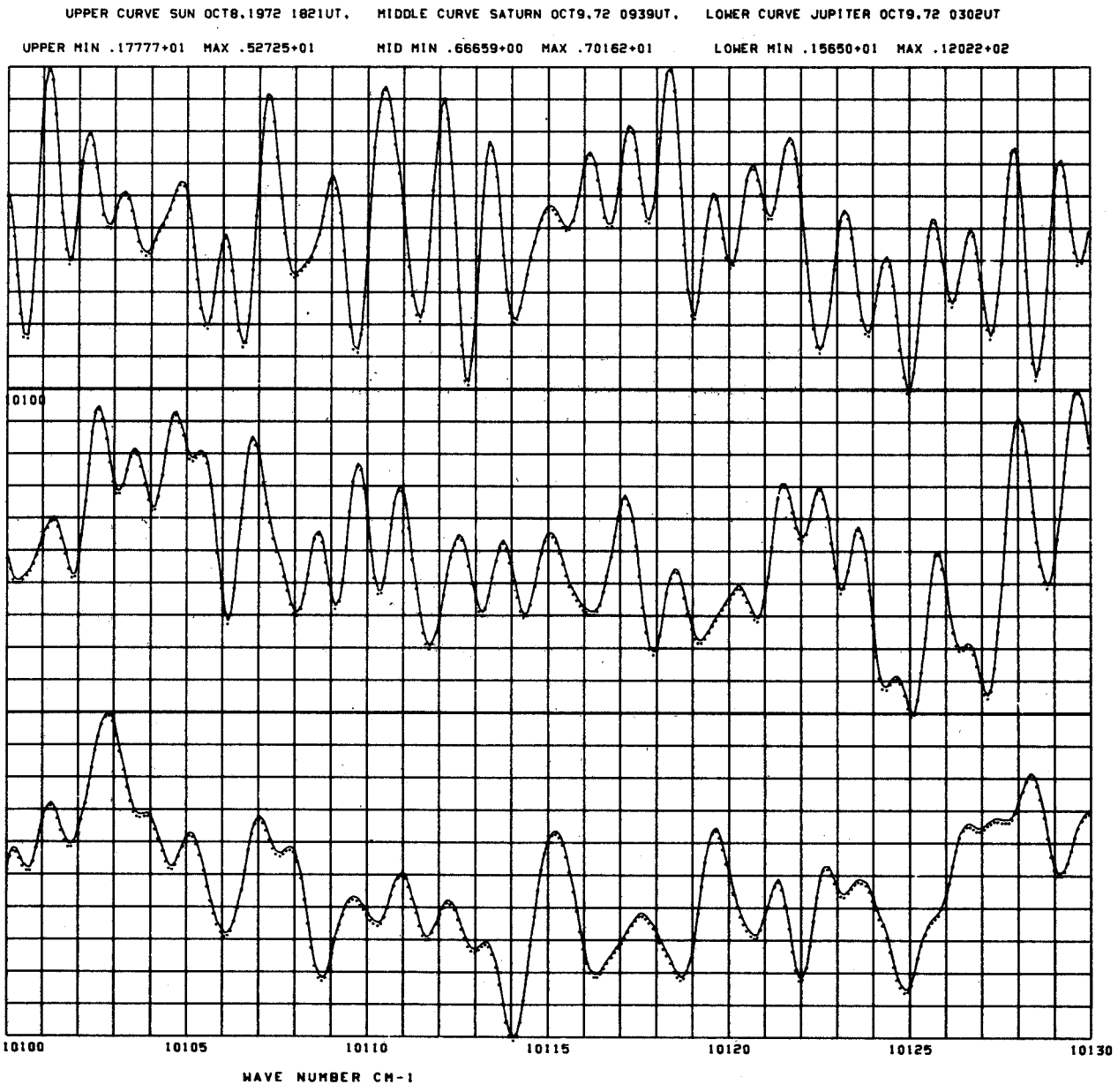

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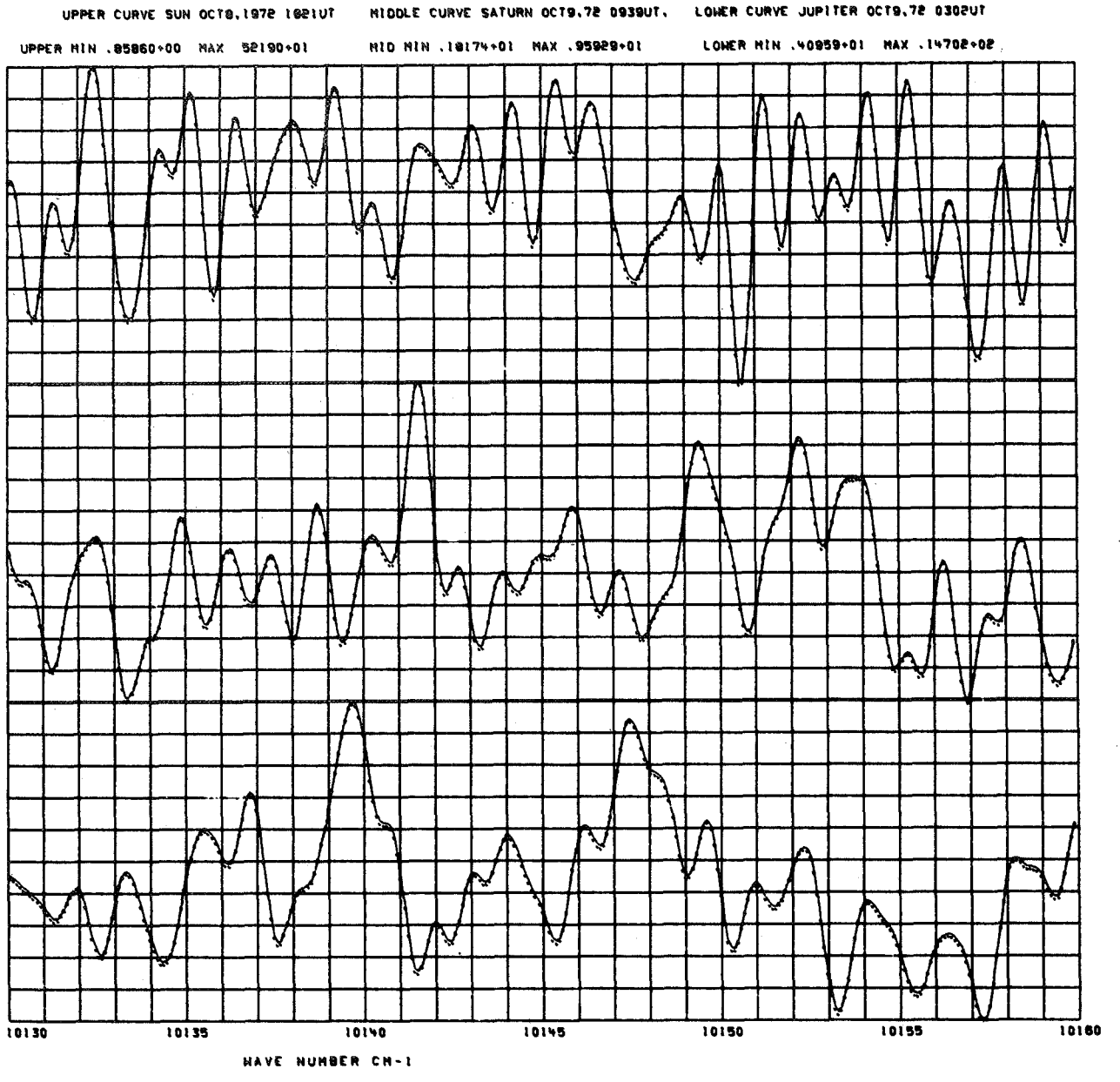

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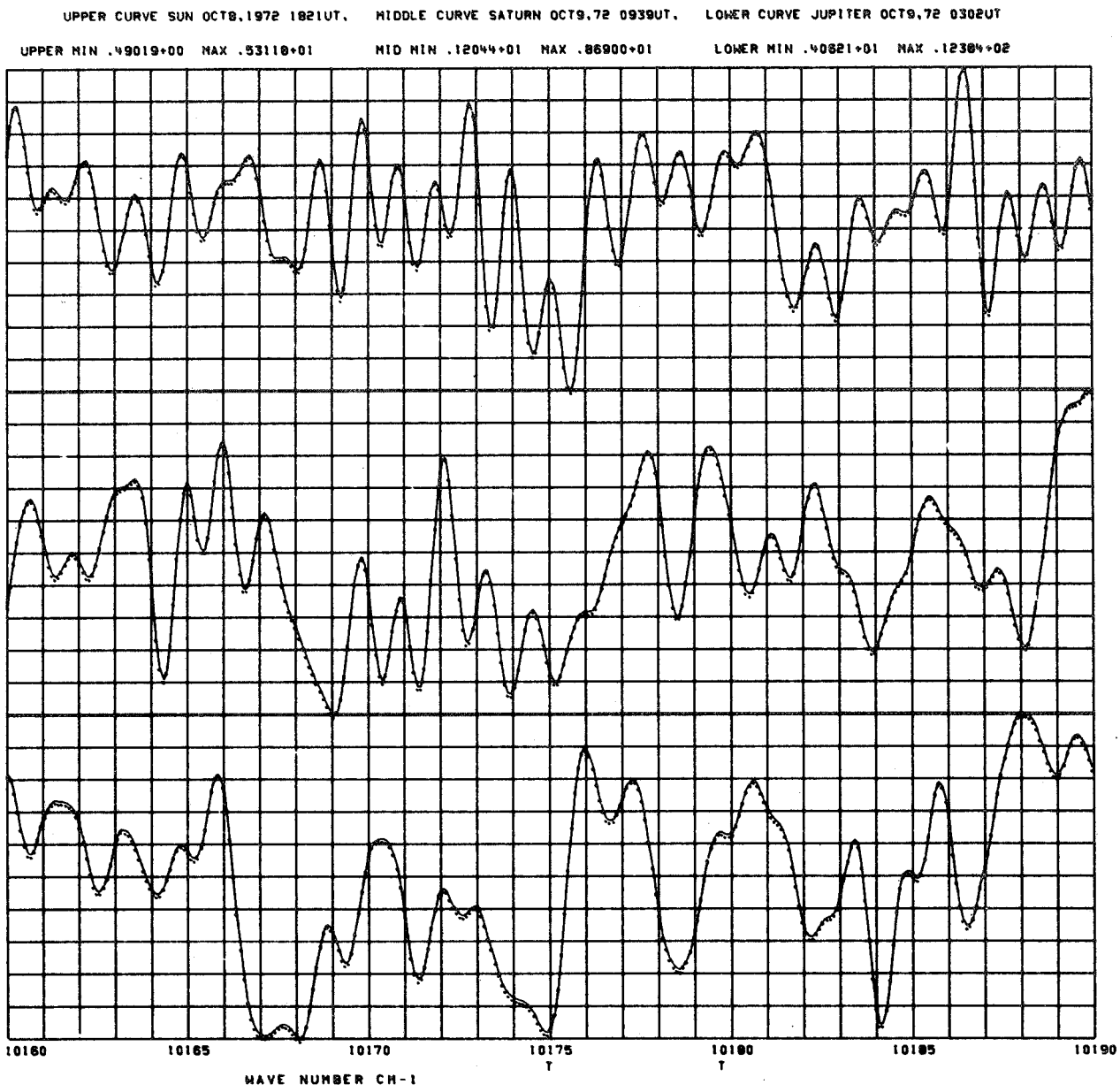

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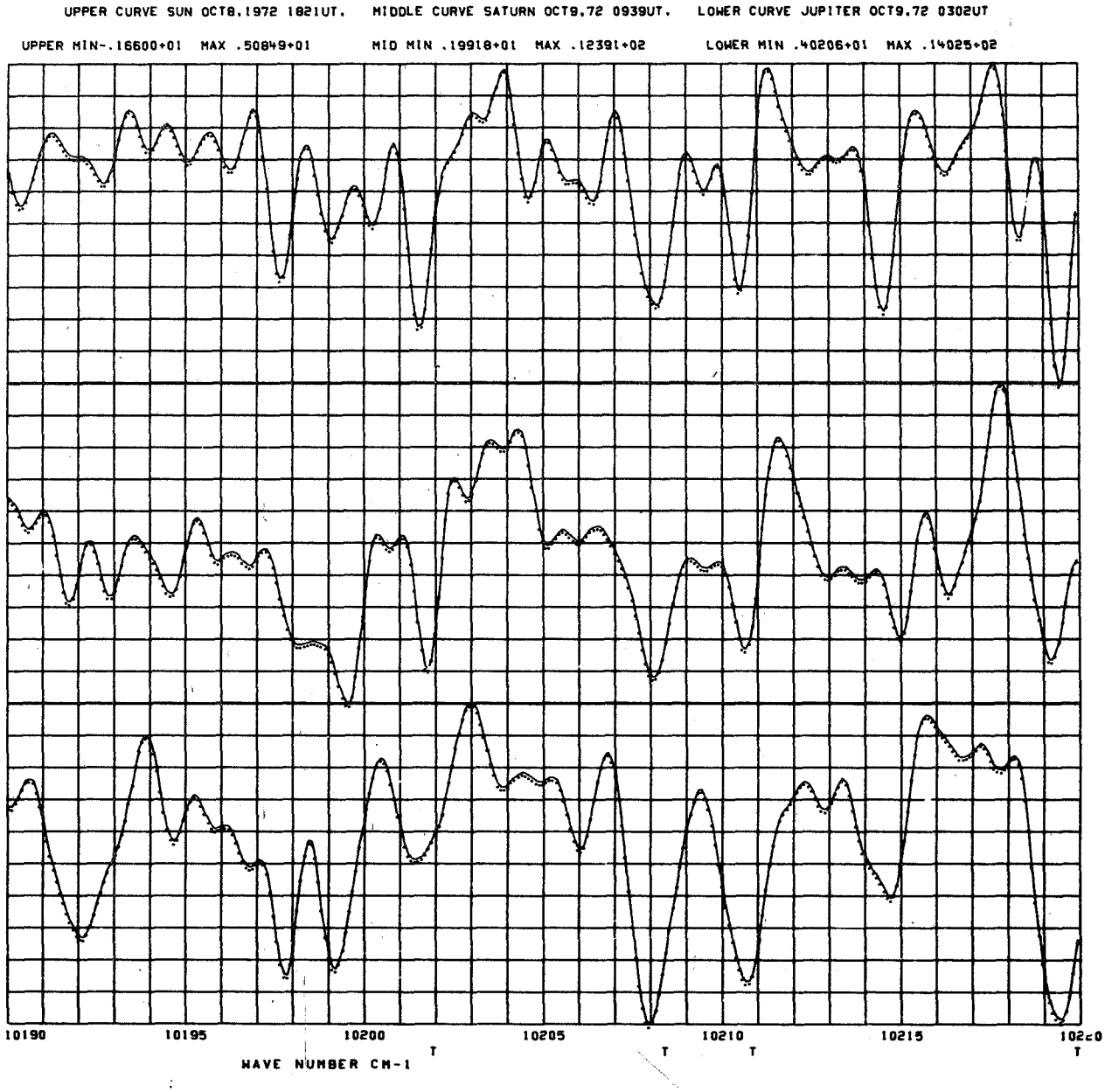

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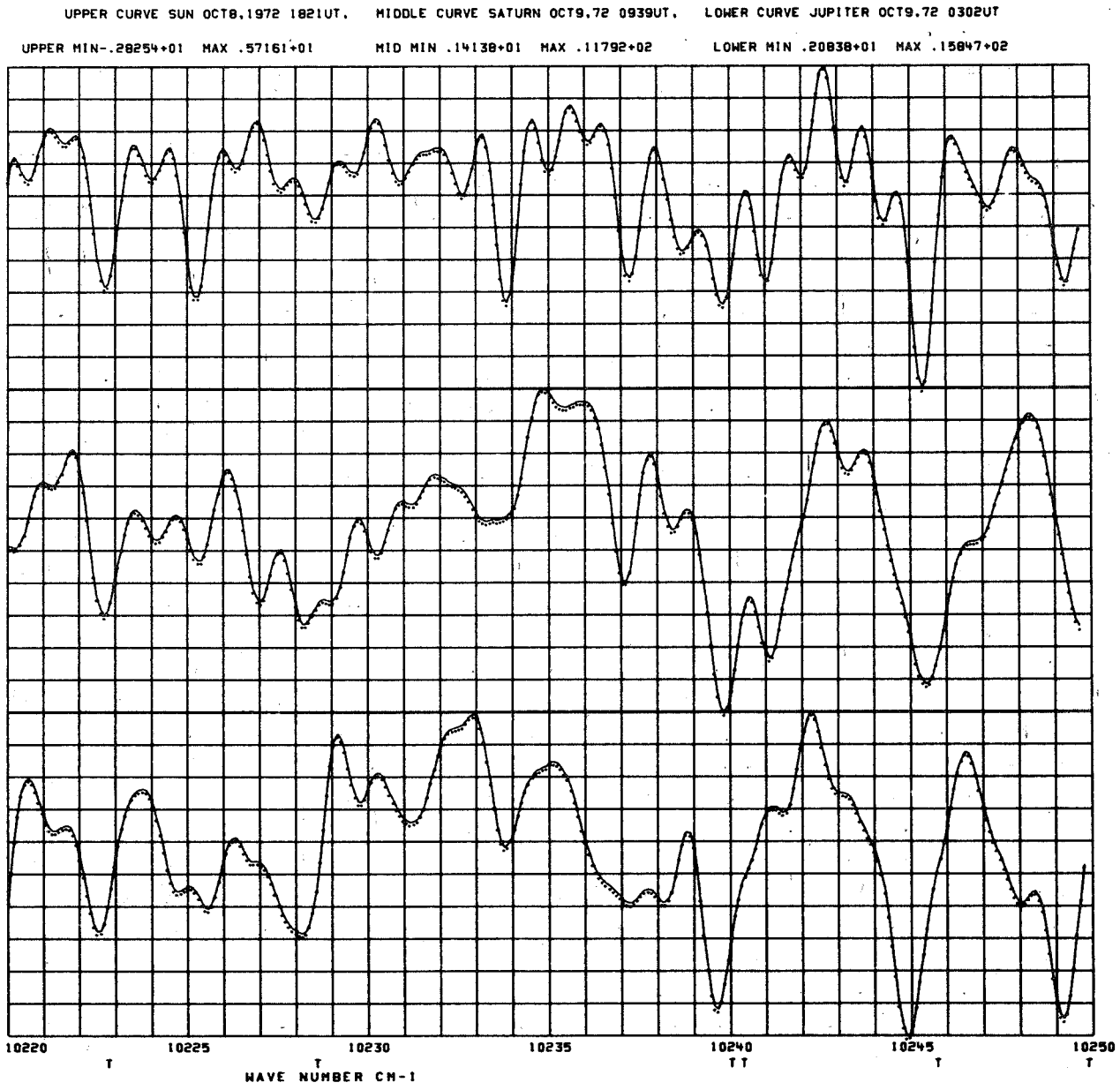

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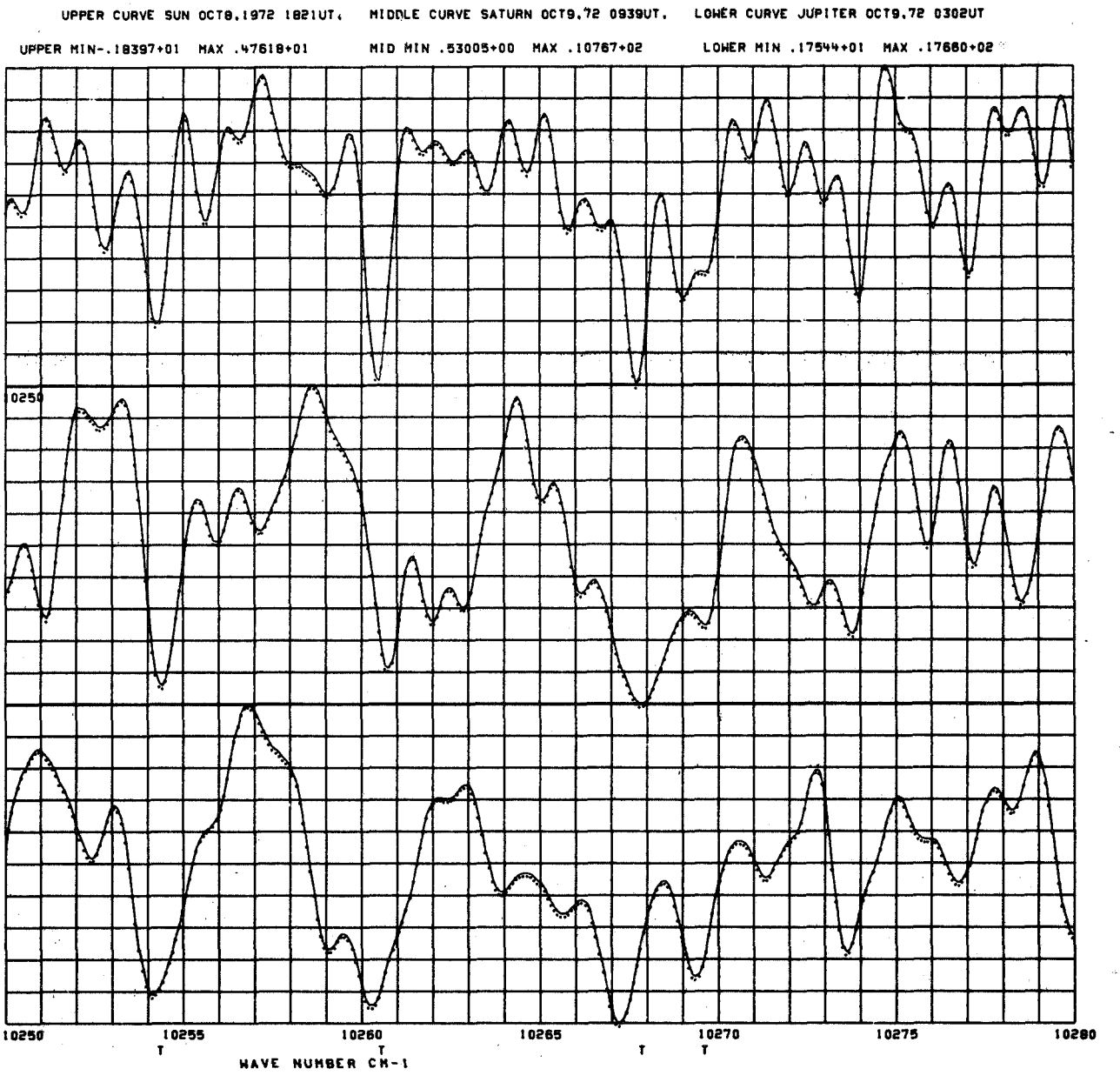

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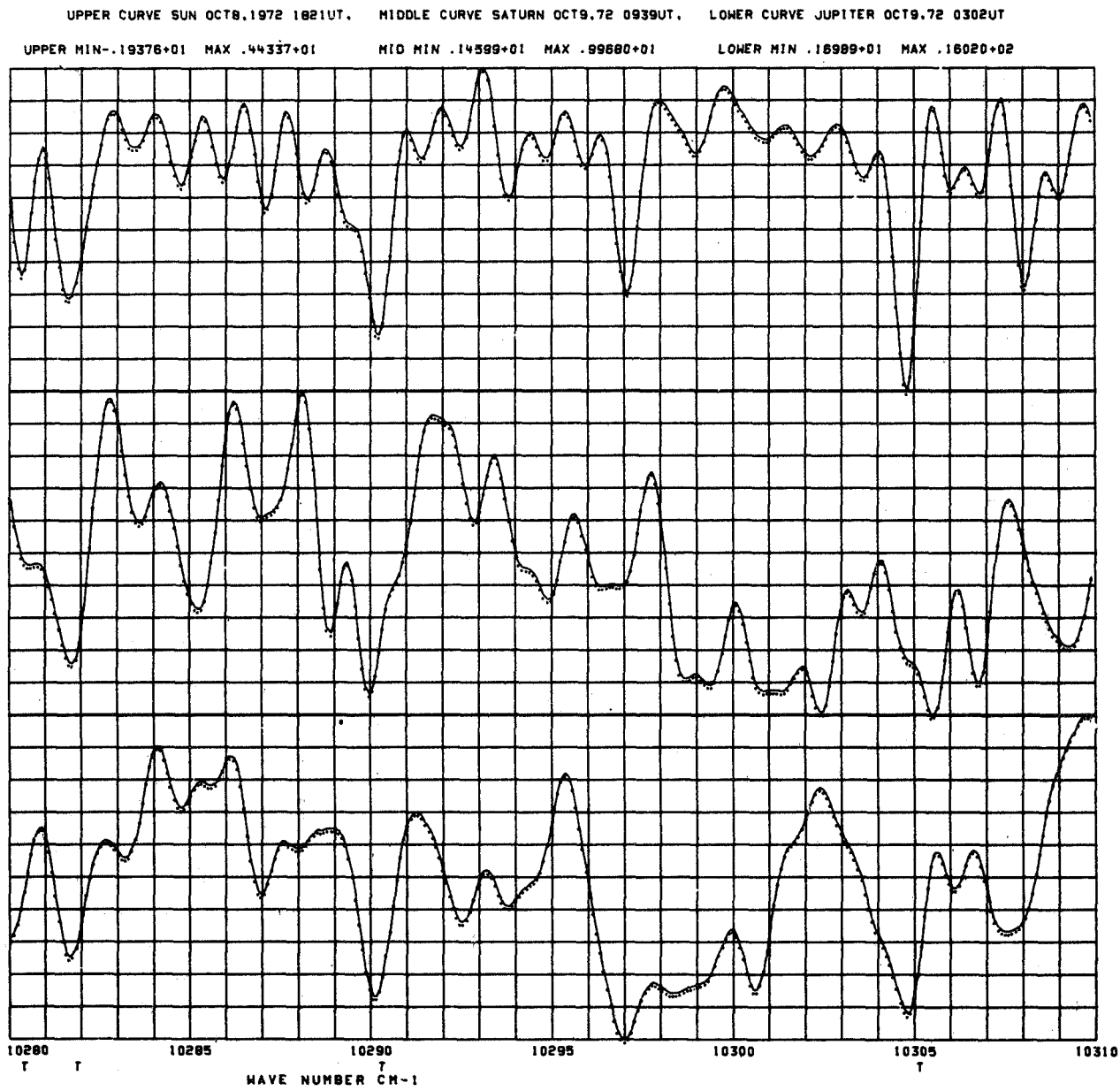

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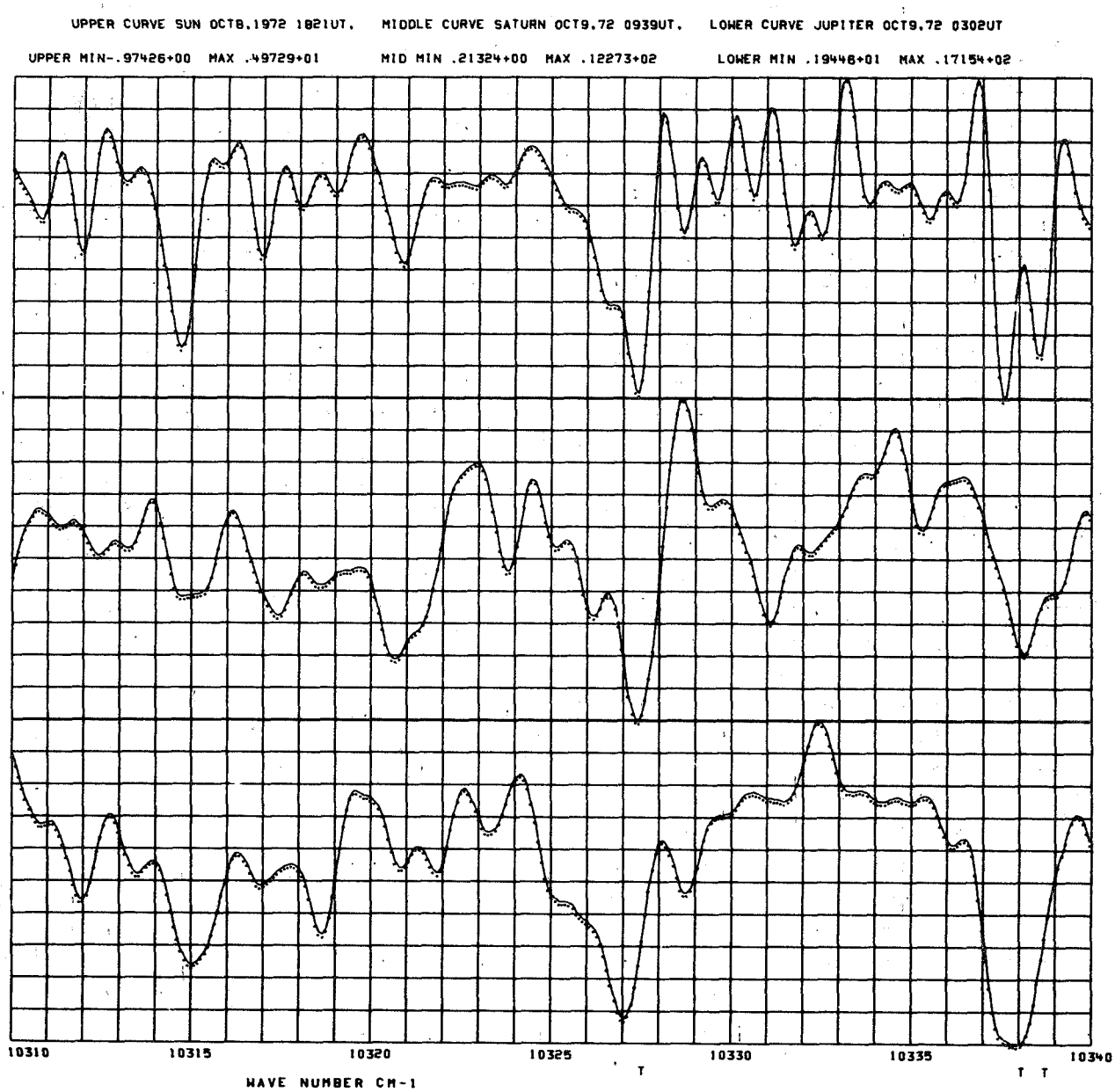

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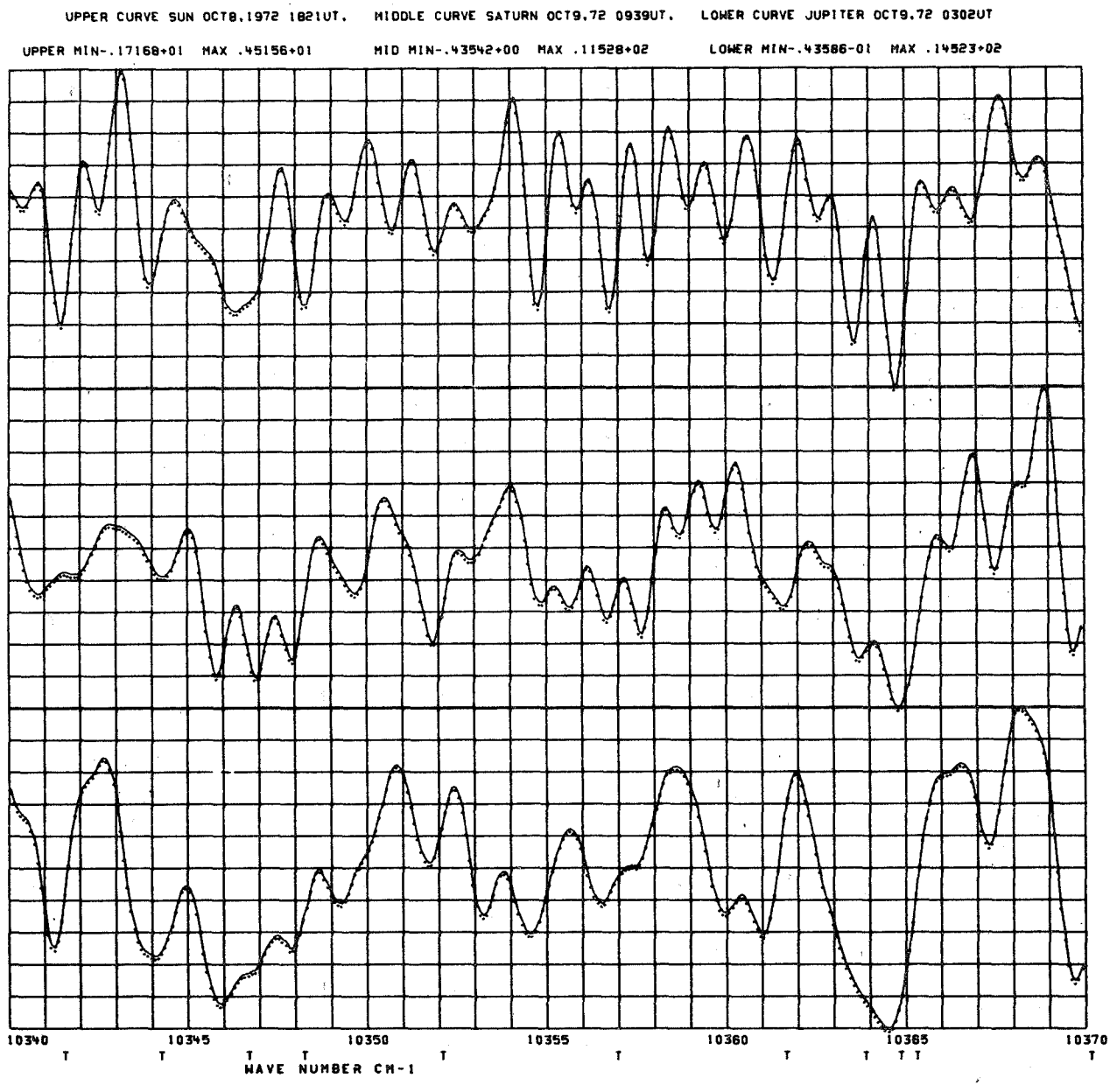


Figure 3 (continued).–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

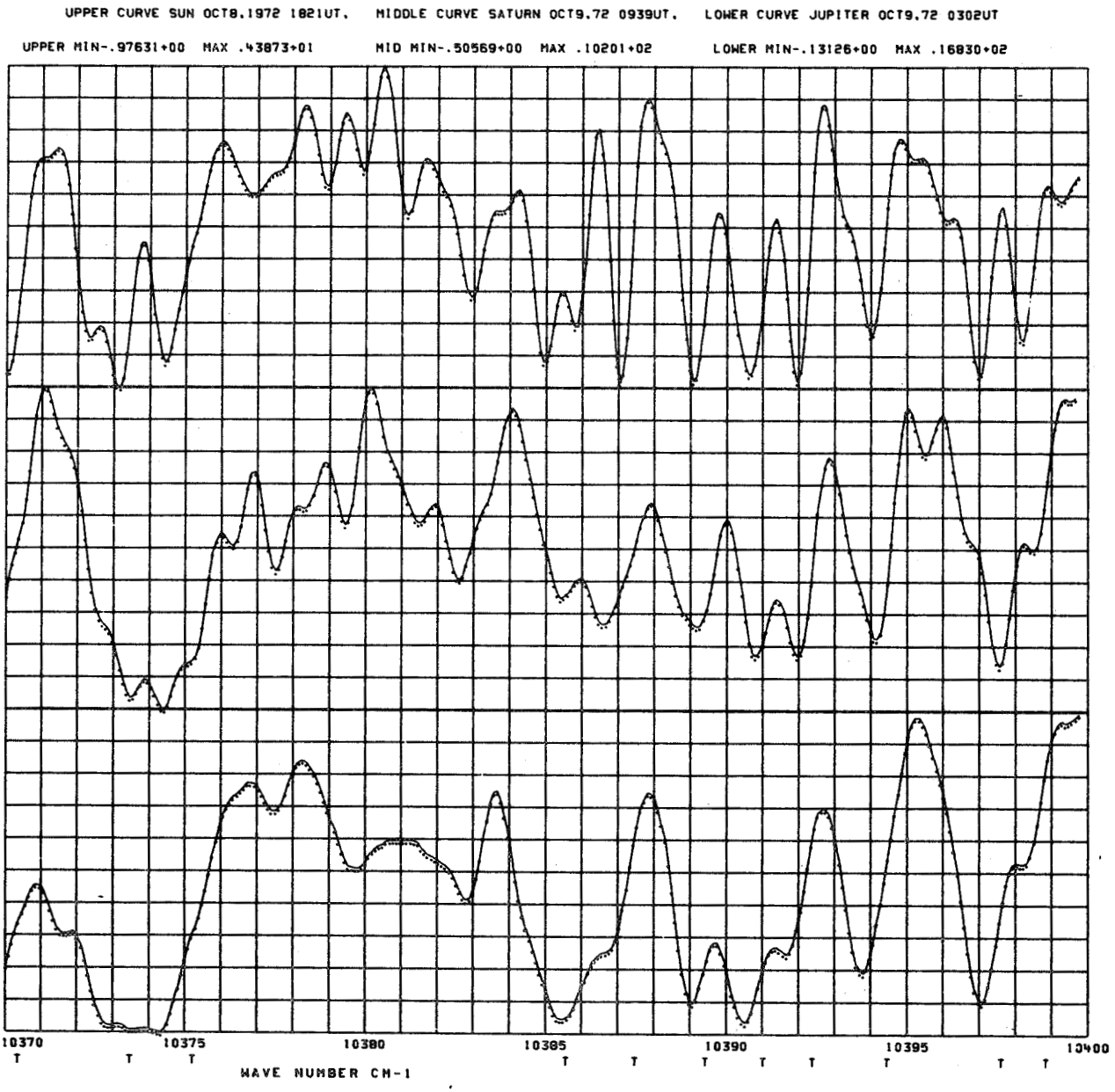
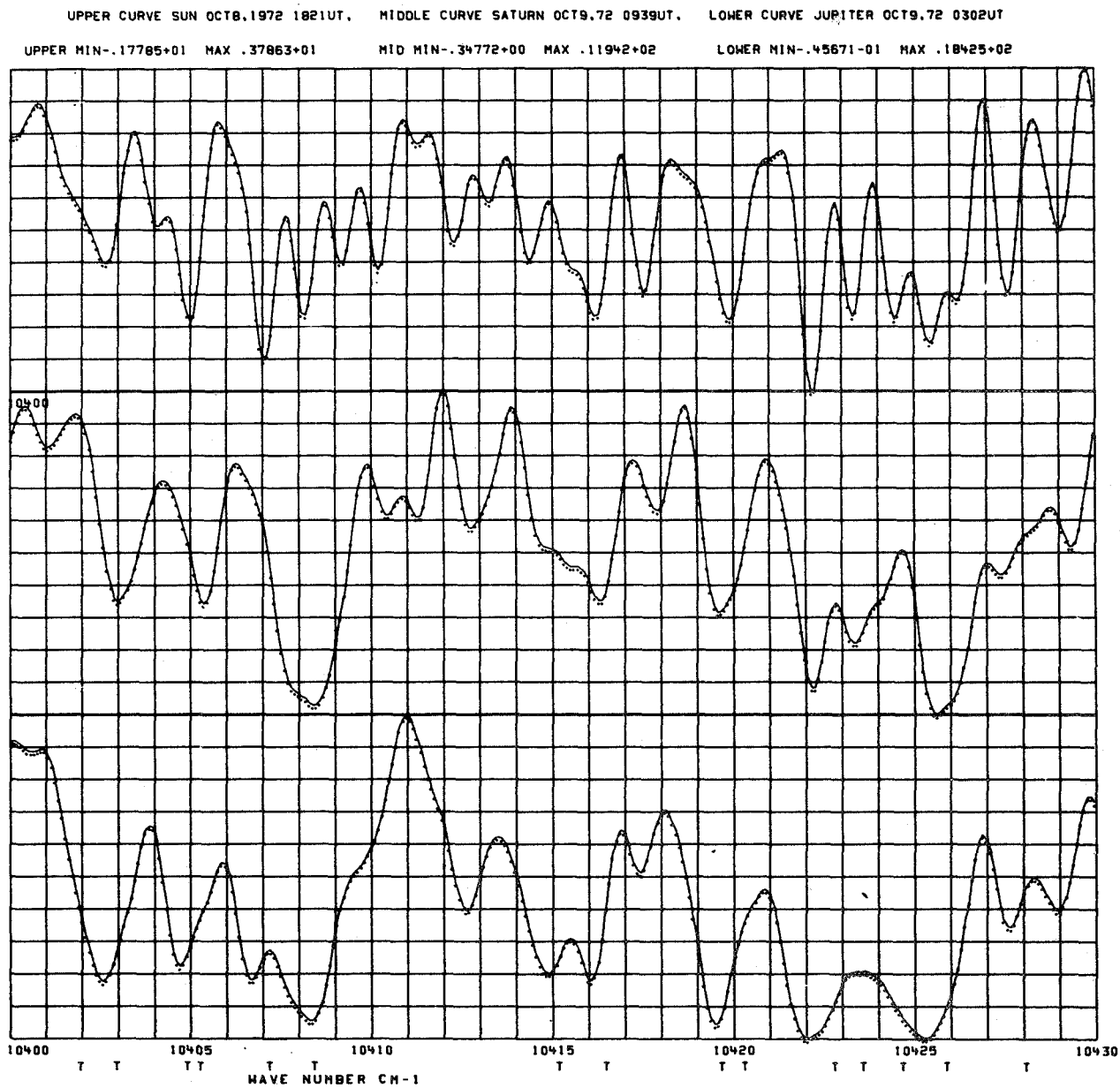


Figure 3 (continued).—Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.



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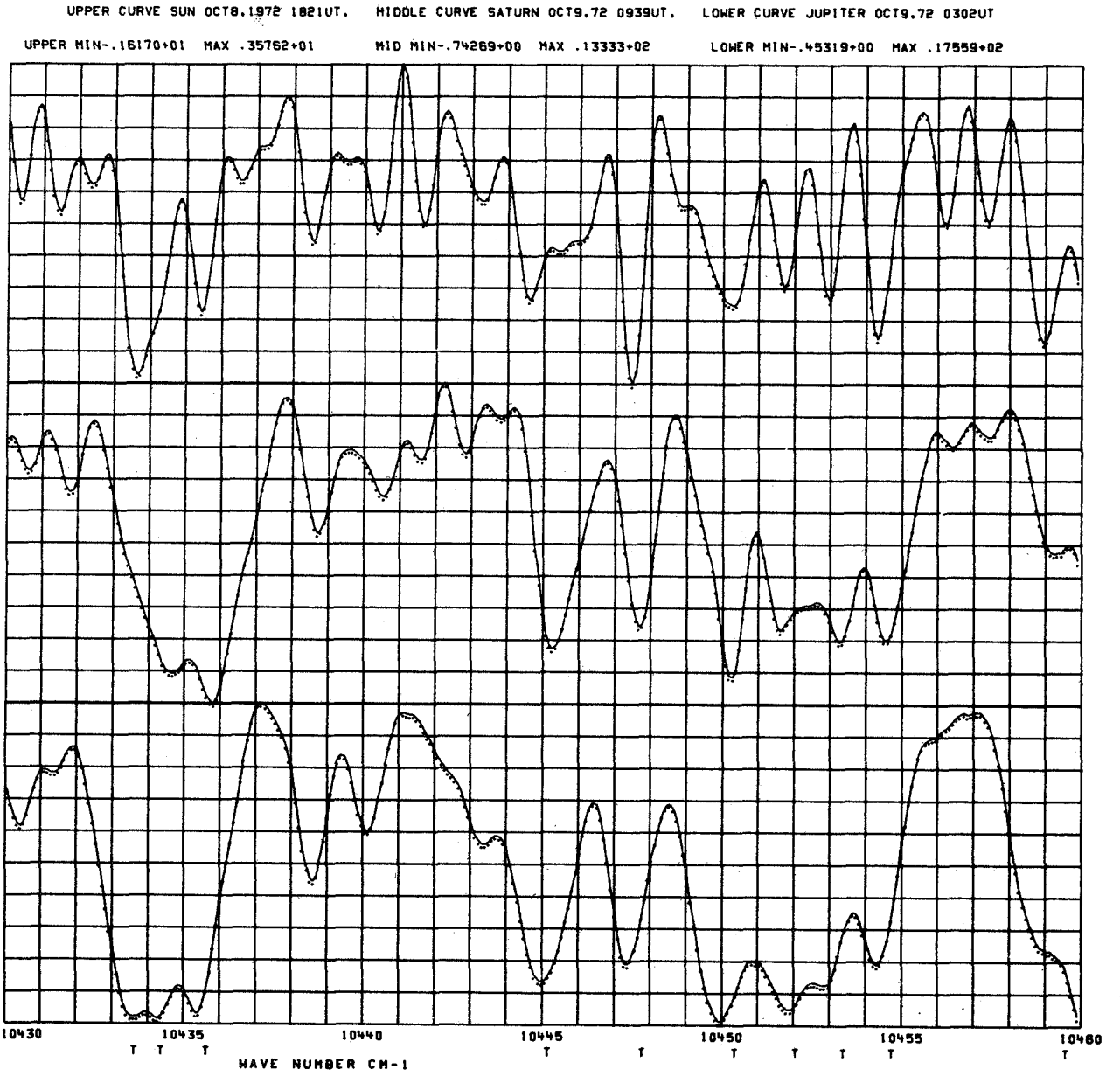


Figure 3 (continued).–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

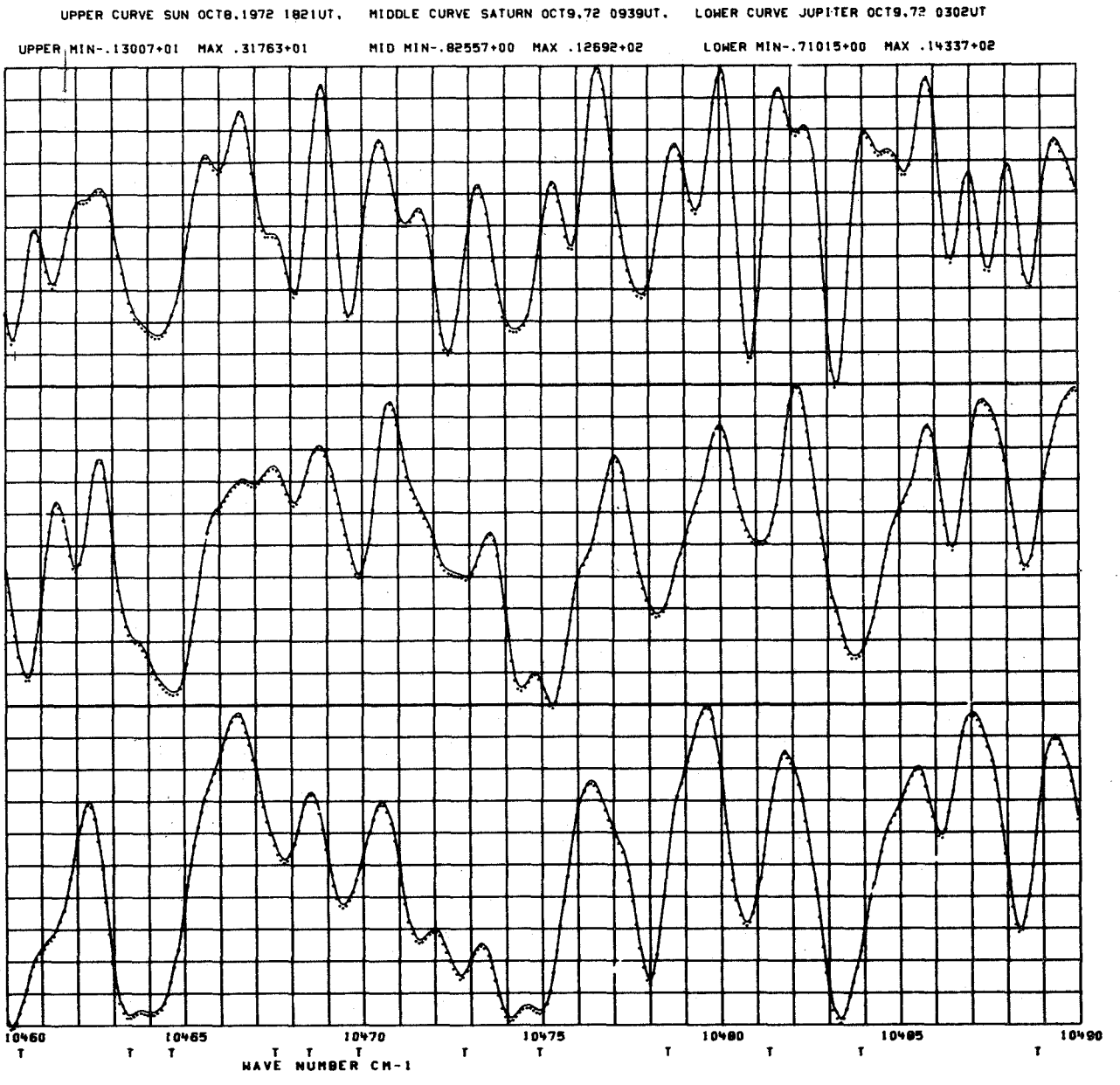
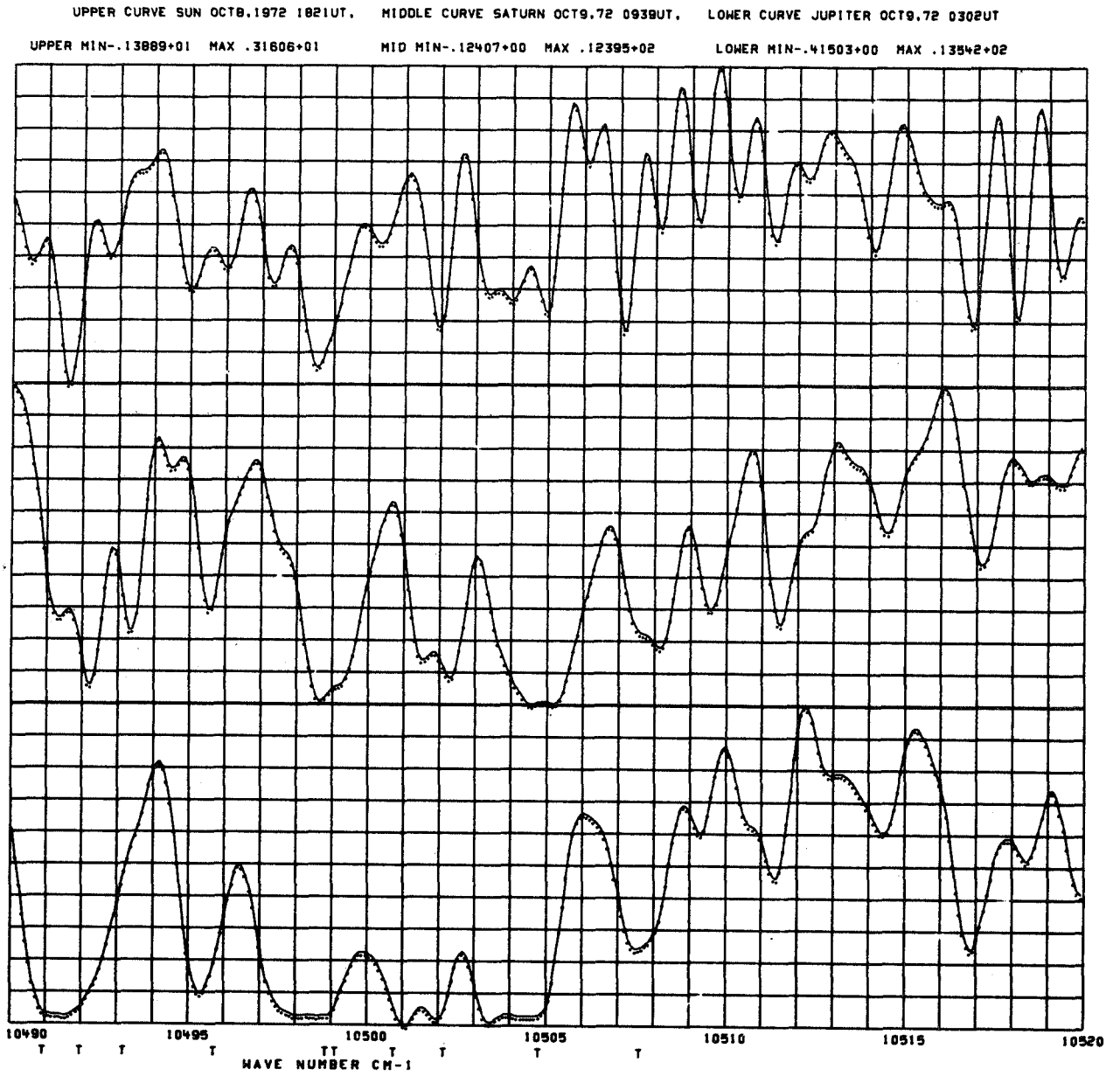


Figure 3 (continued).–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.



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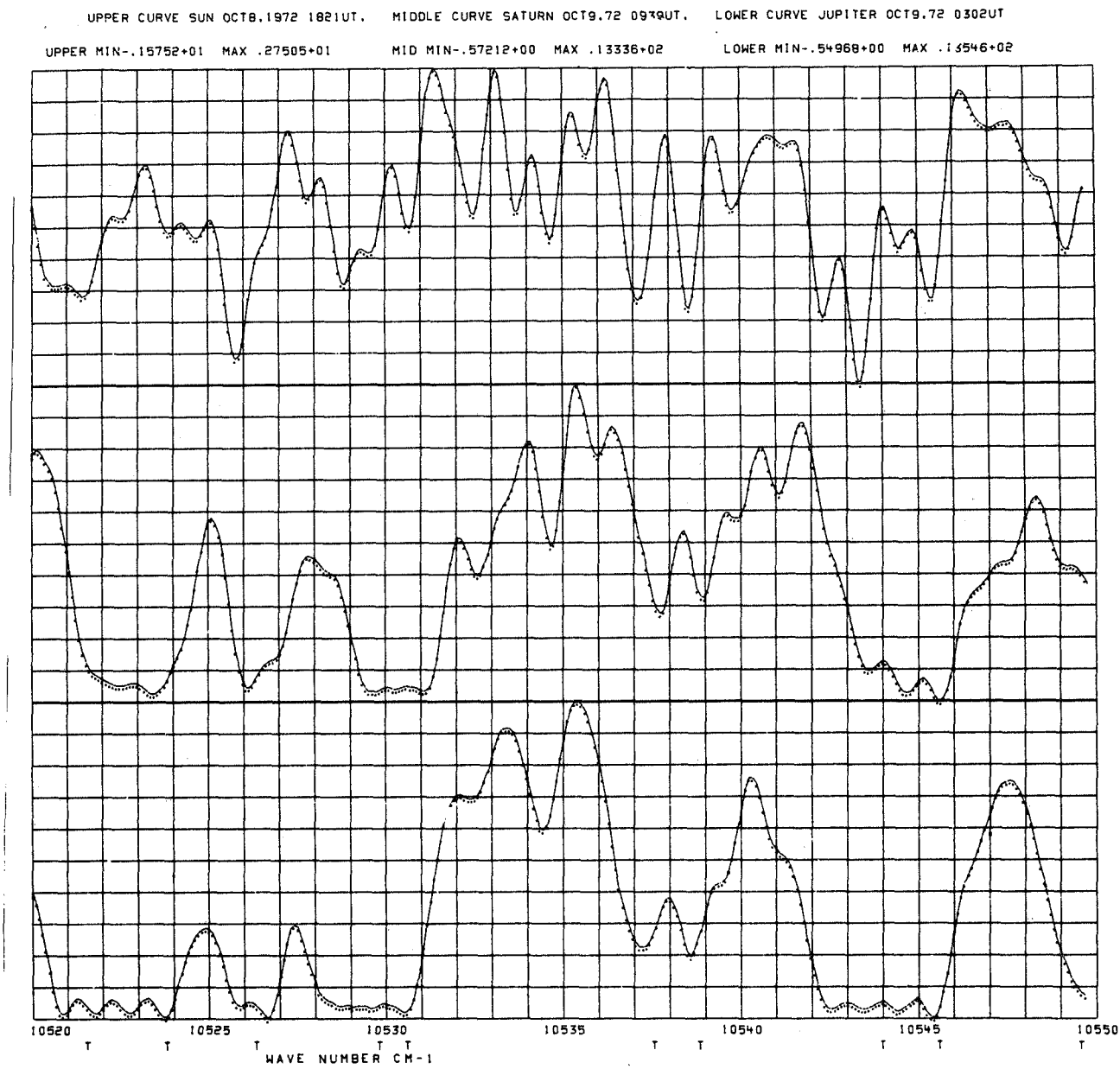

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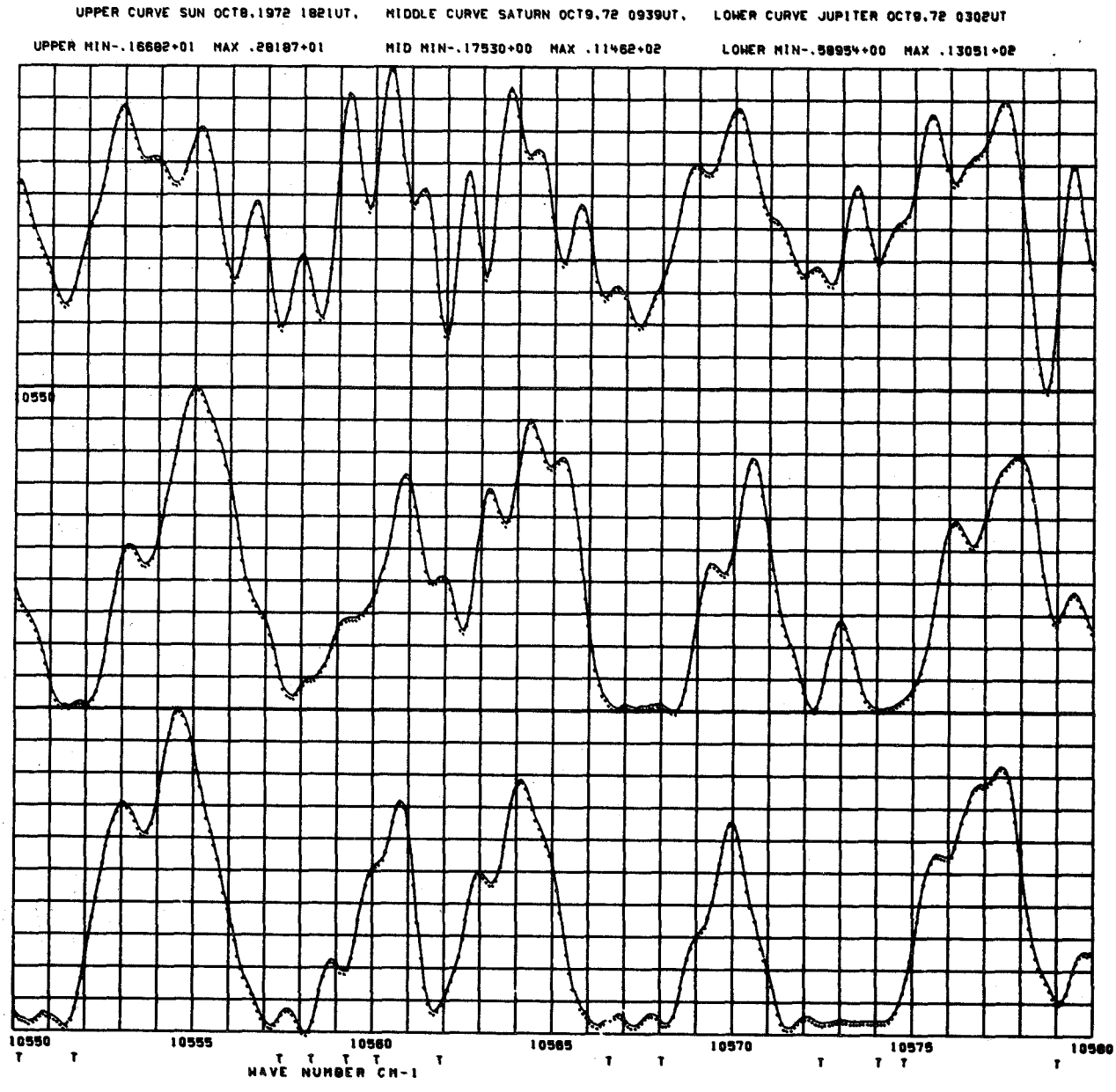
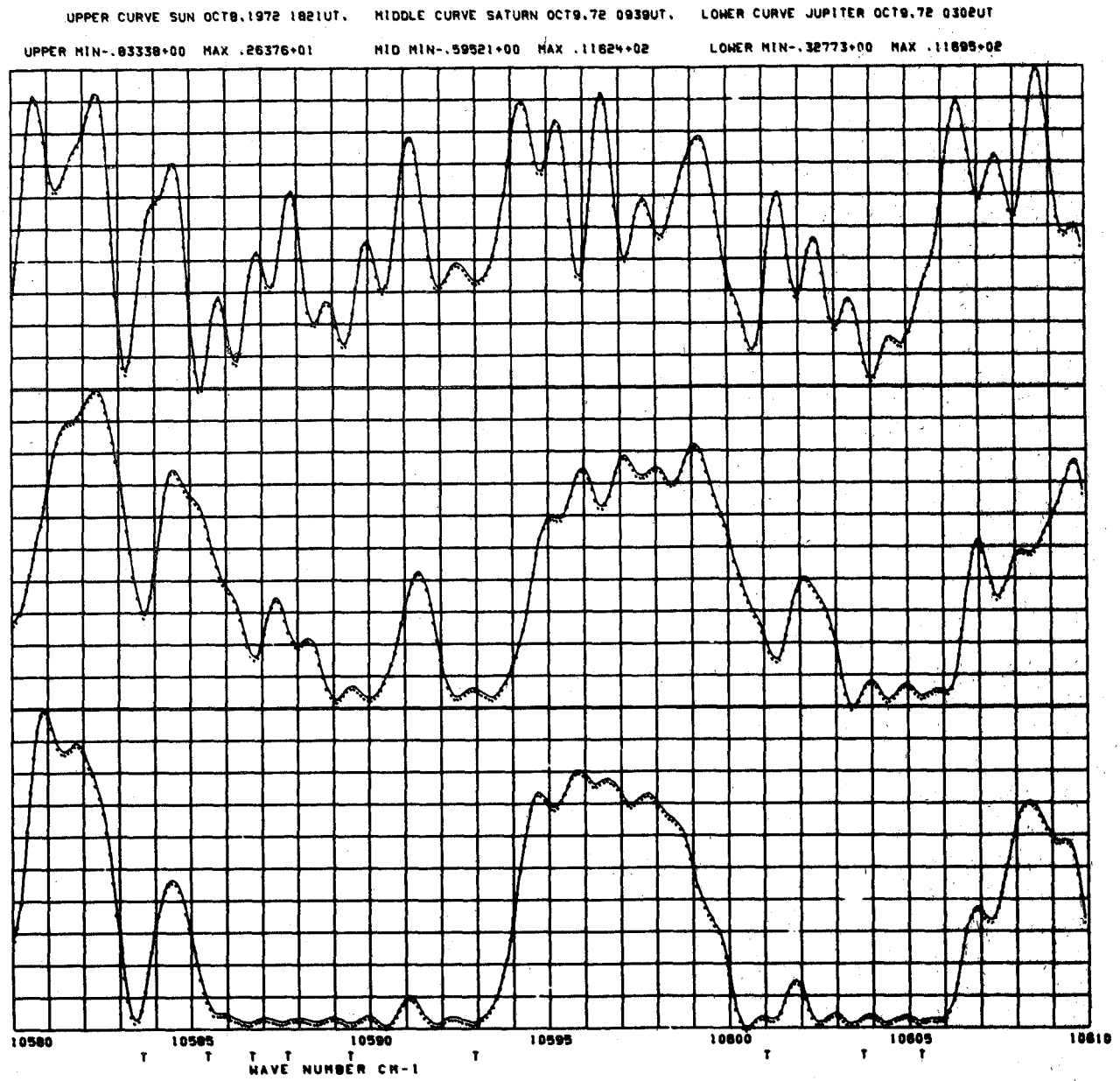


Figure 3 (continued).—Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.



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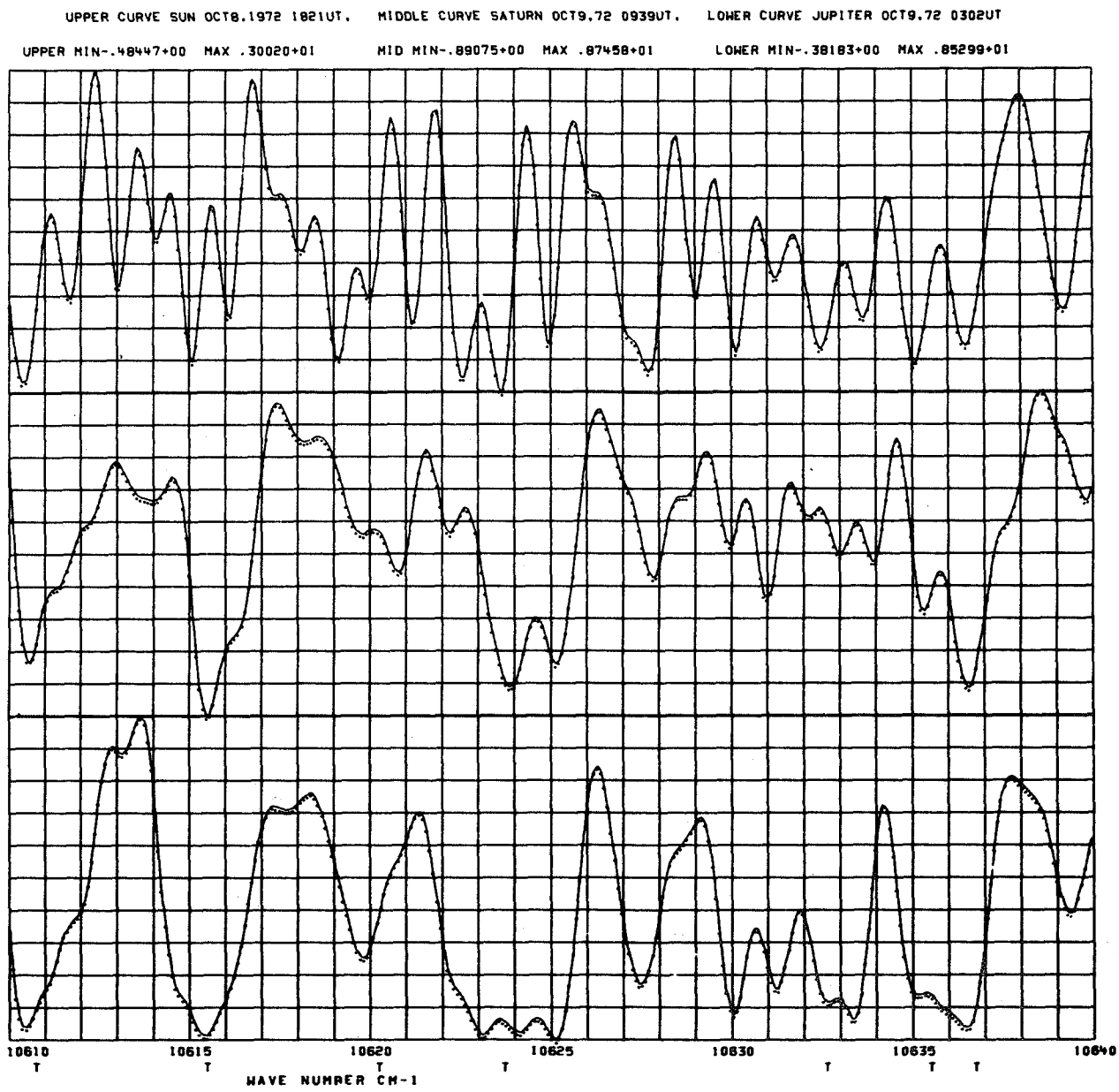


Figure 3 (continued).—Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

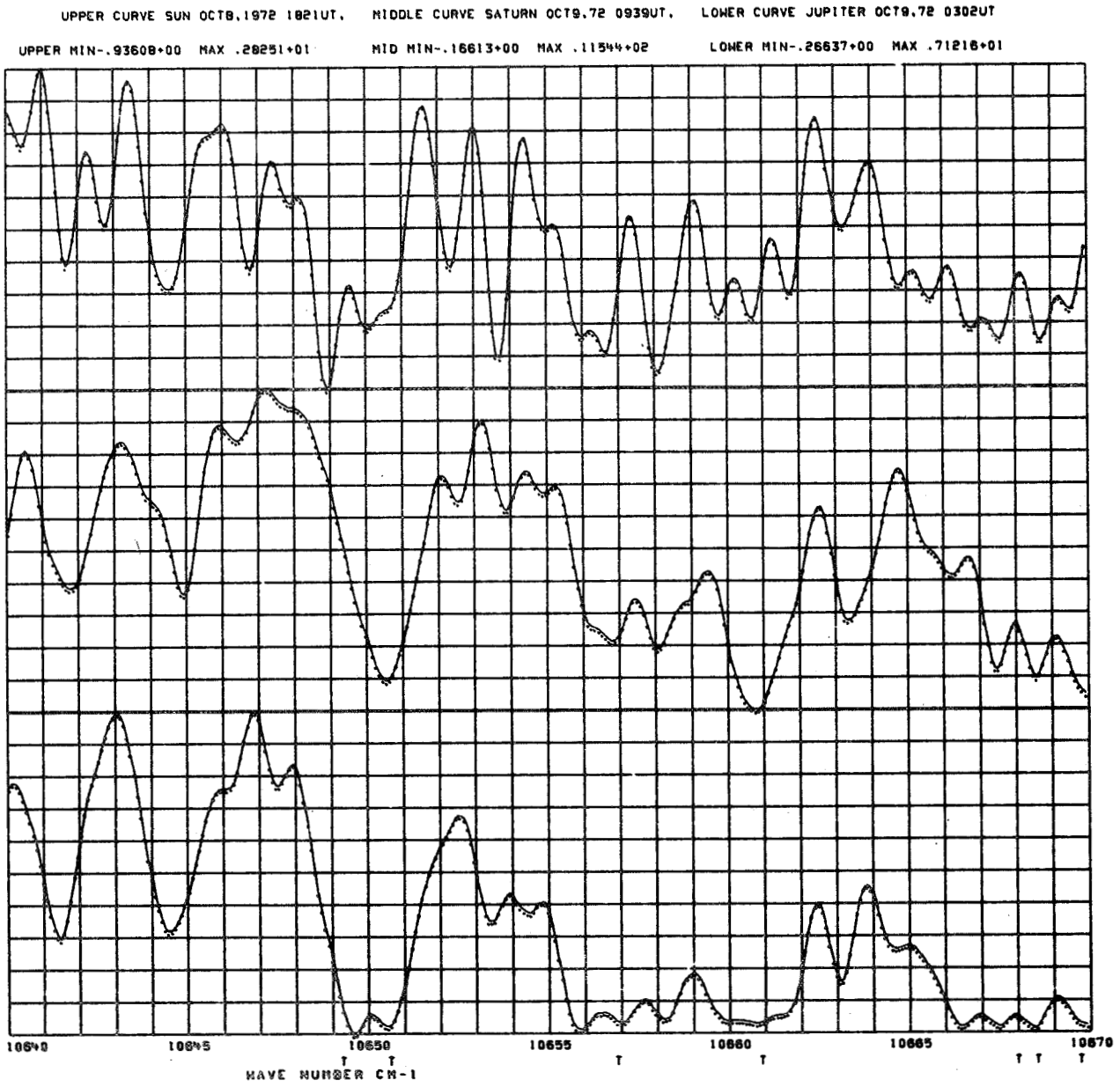


Figure 3 (continued).—Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

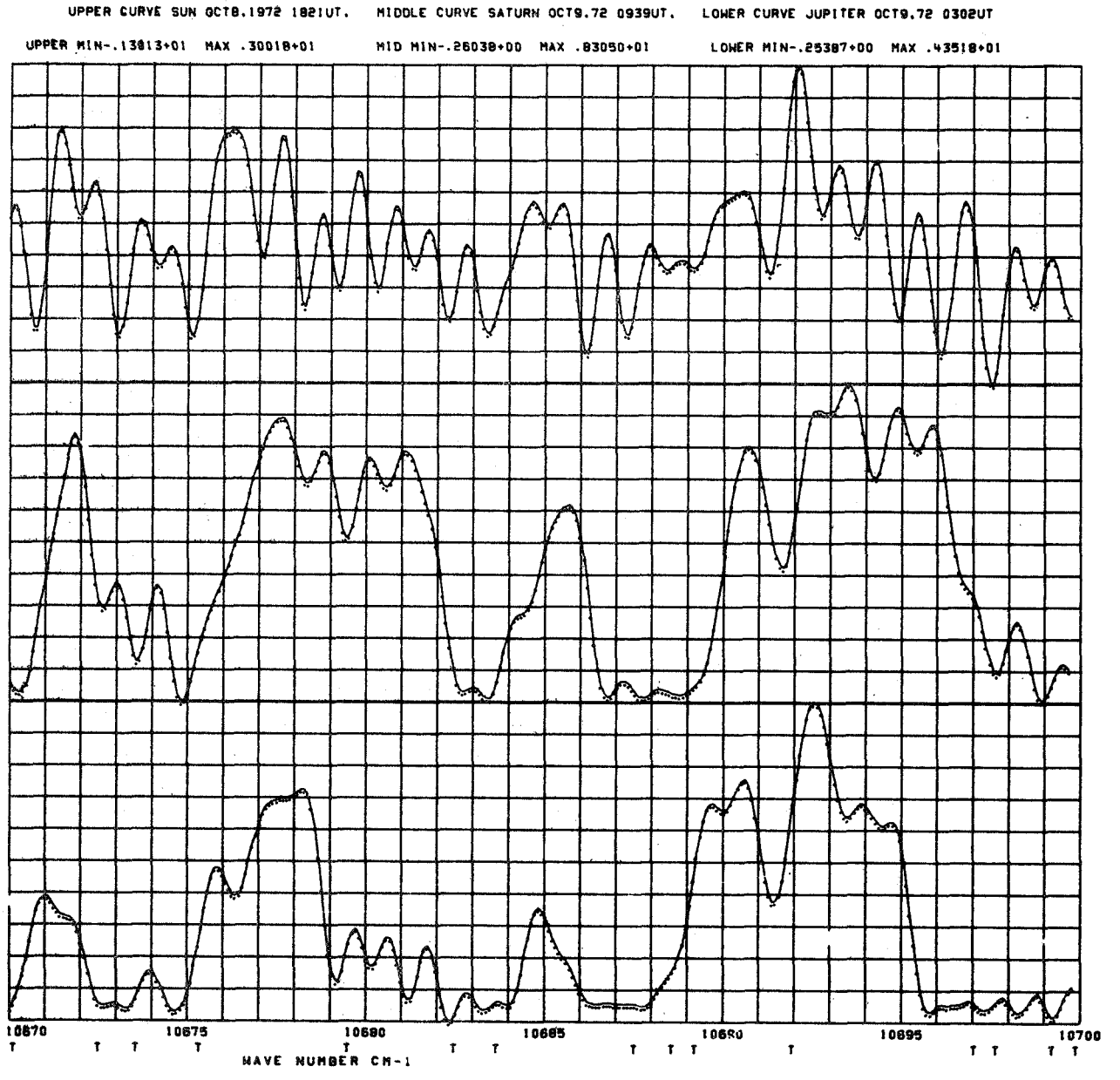


Figure 3 (continued).–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

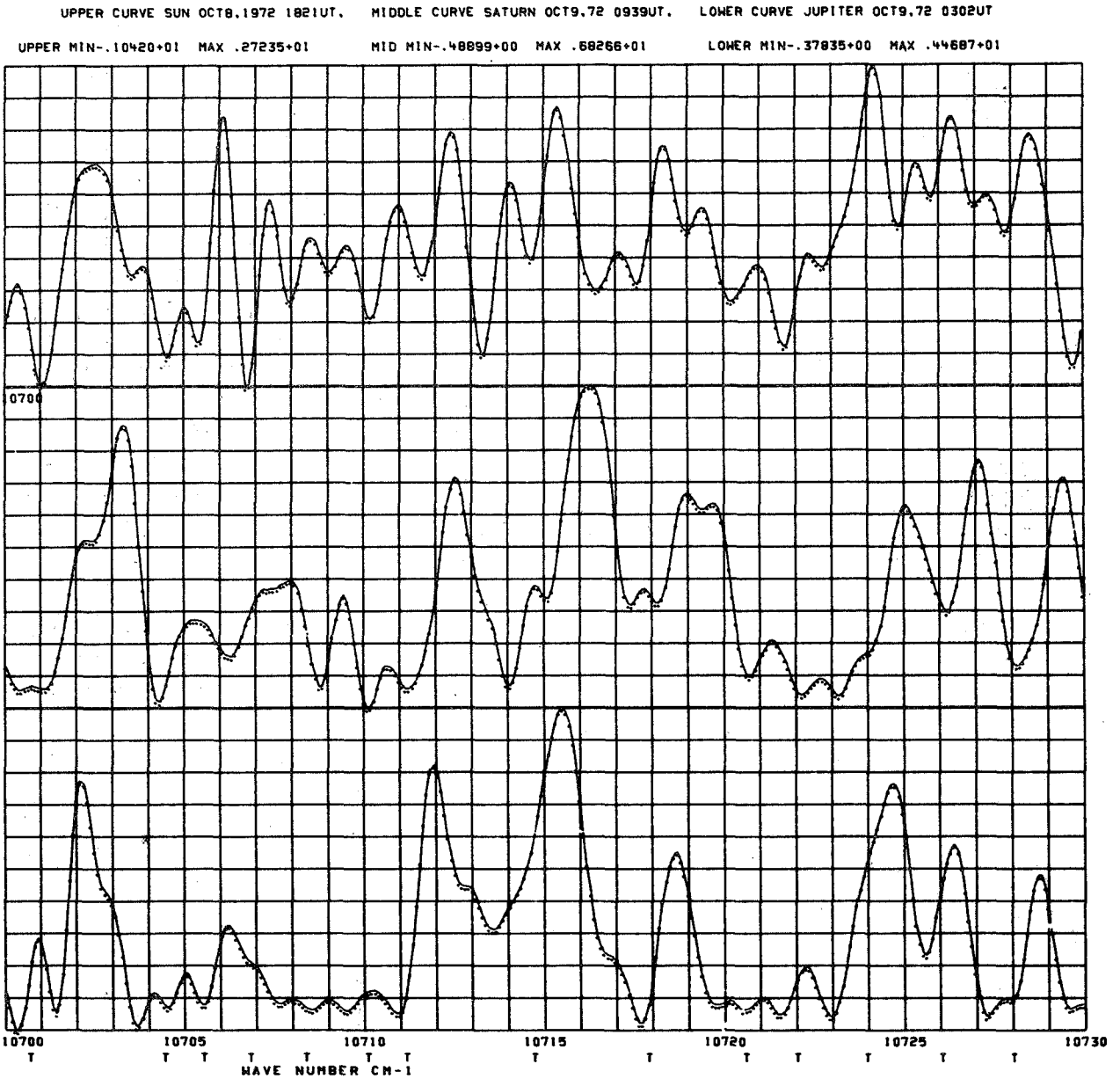


Figure 3 (continued).–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

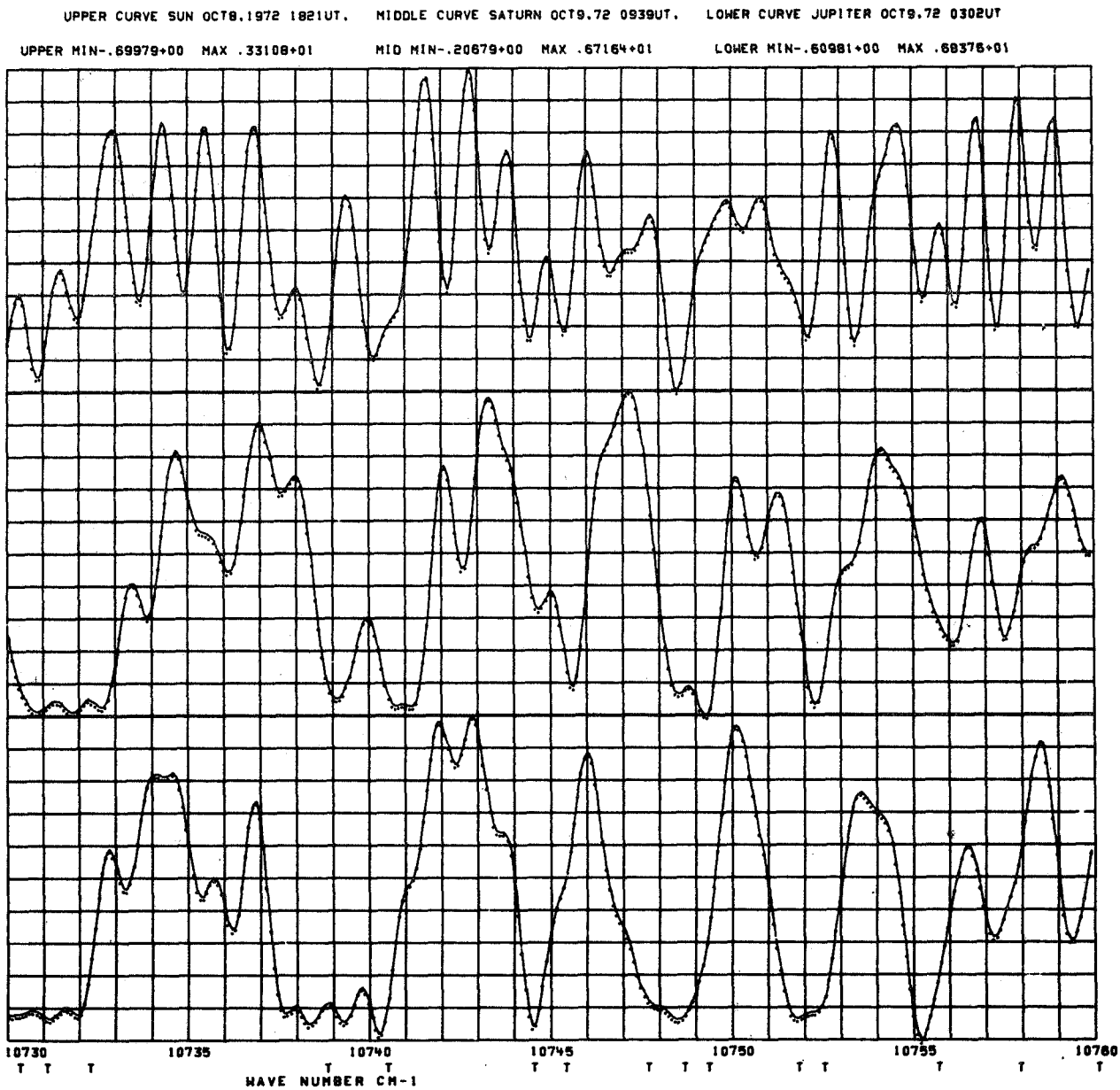


Figure 3 (concluded).–Near-infrared spectra of Saturn, Jupiter, and the Sun compared at a resolution of 0.5 cm^{-1}.

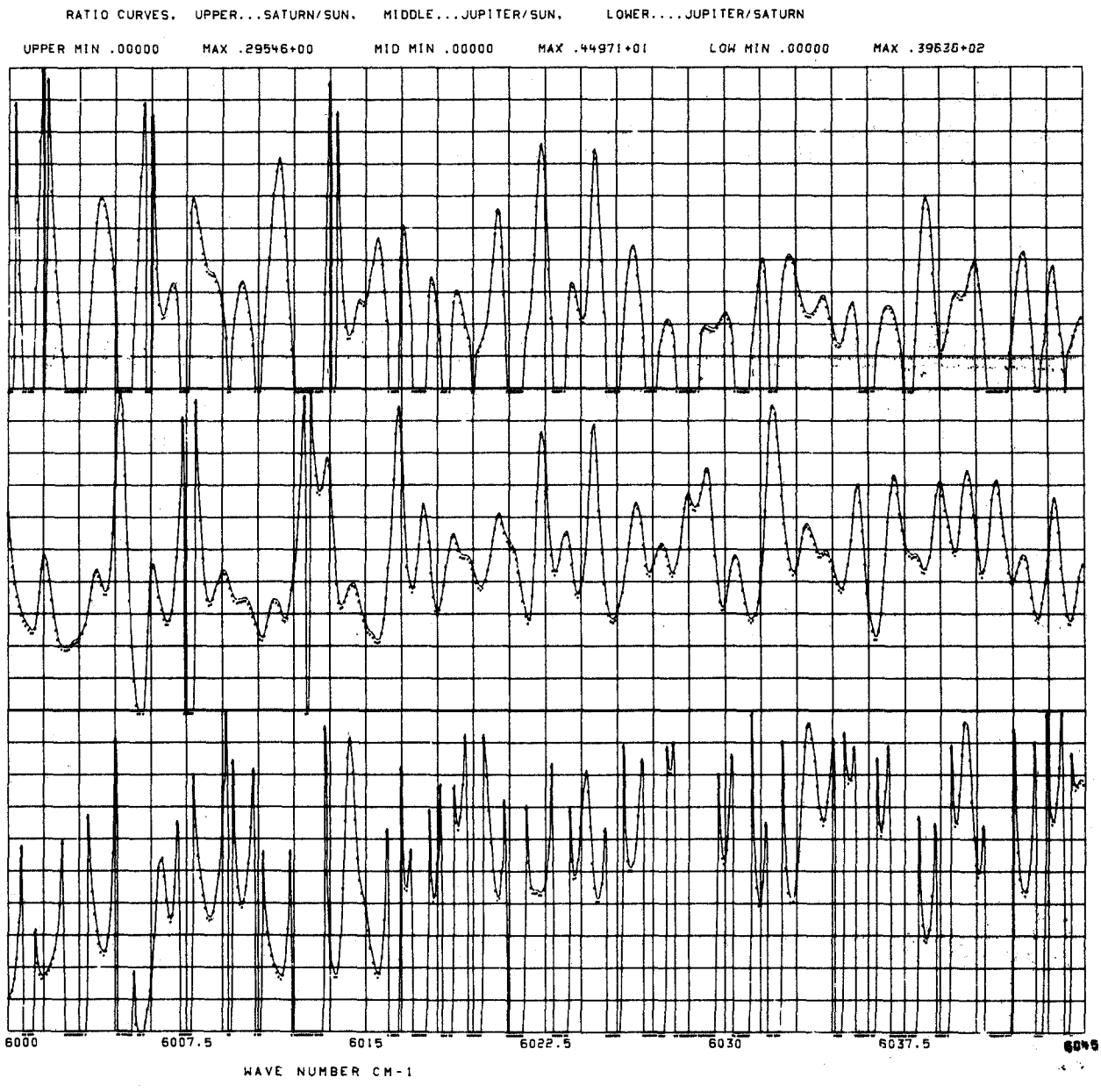


Figure 4.–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

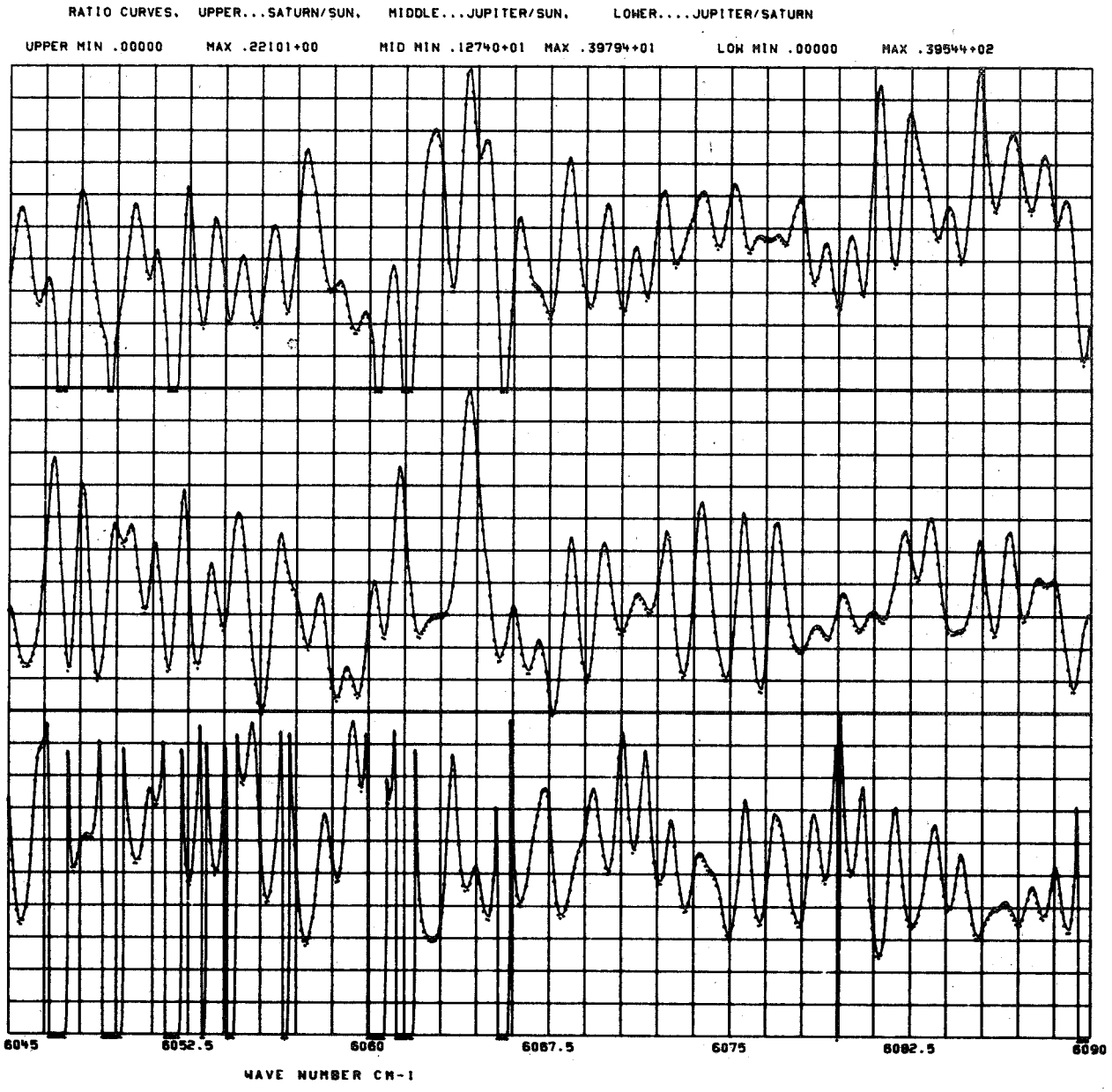


Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

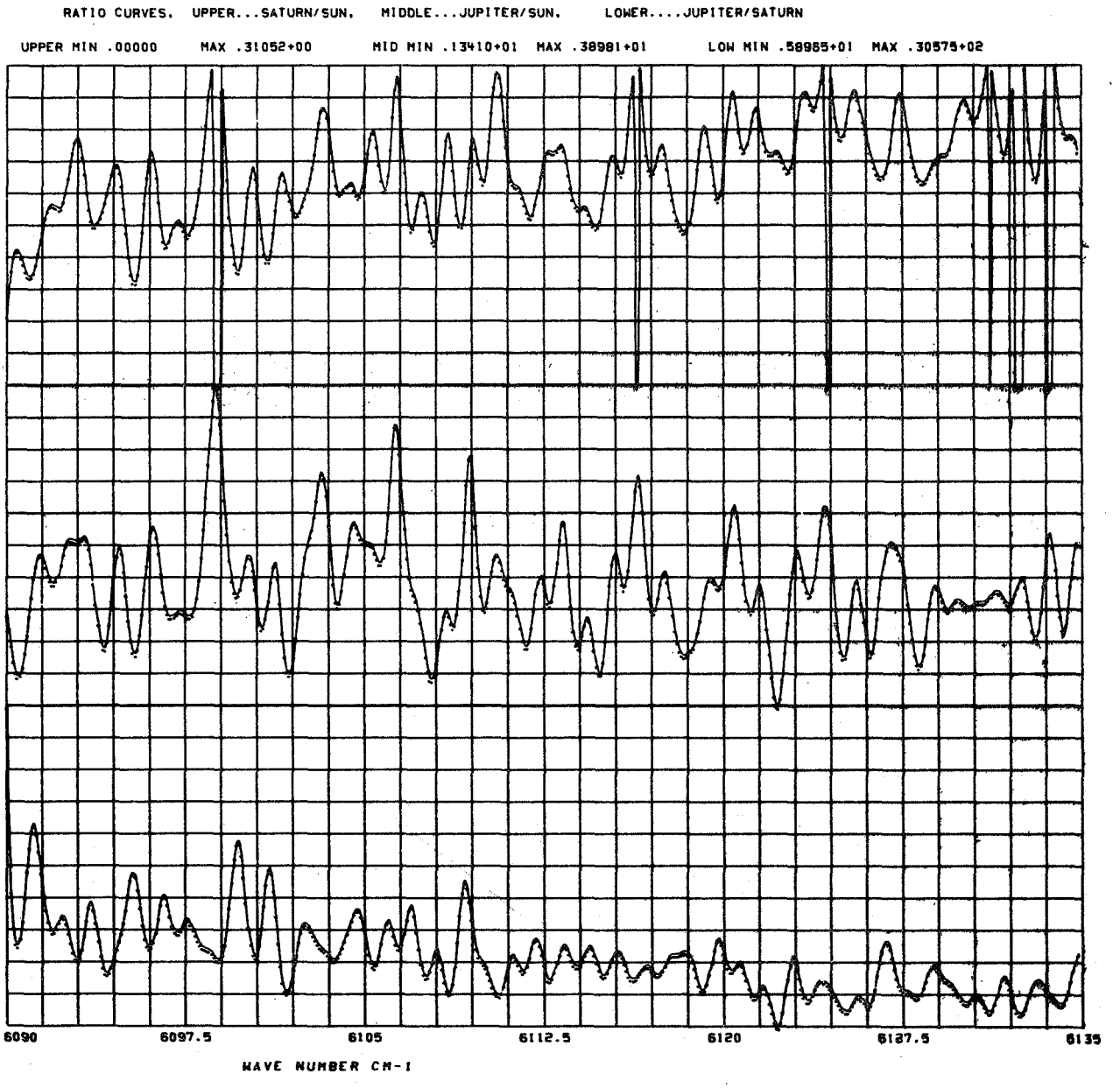


Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

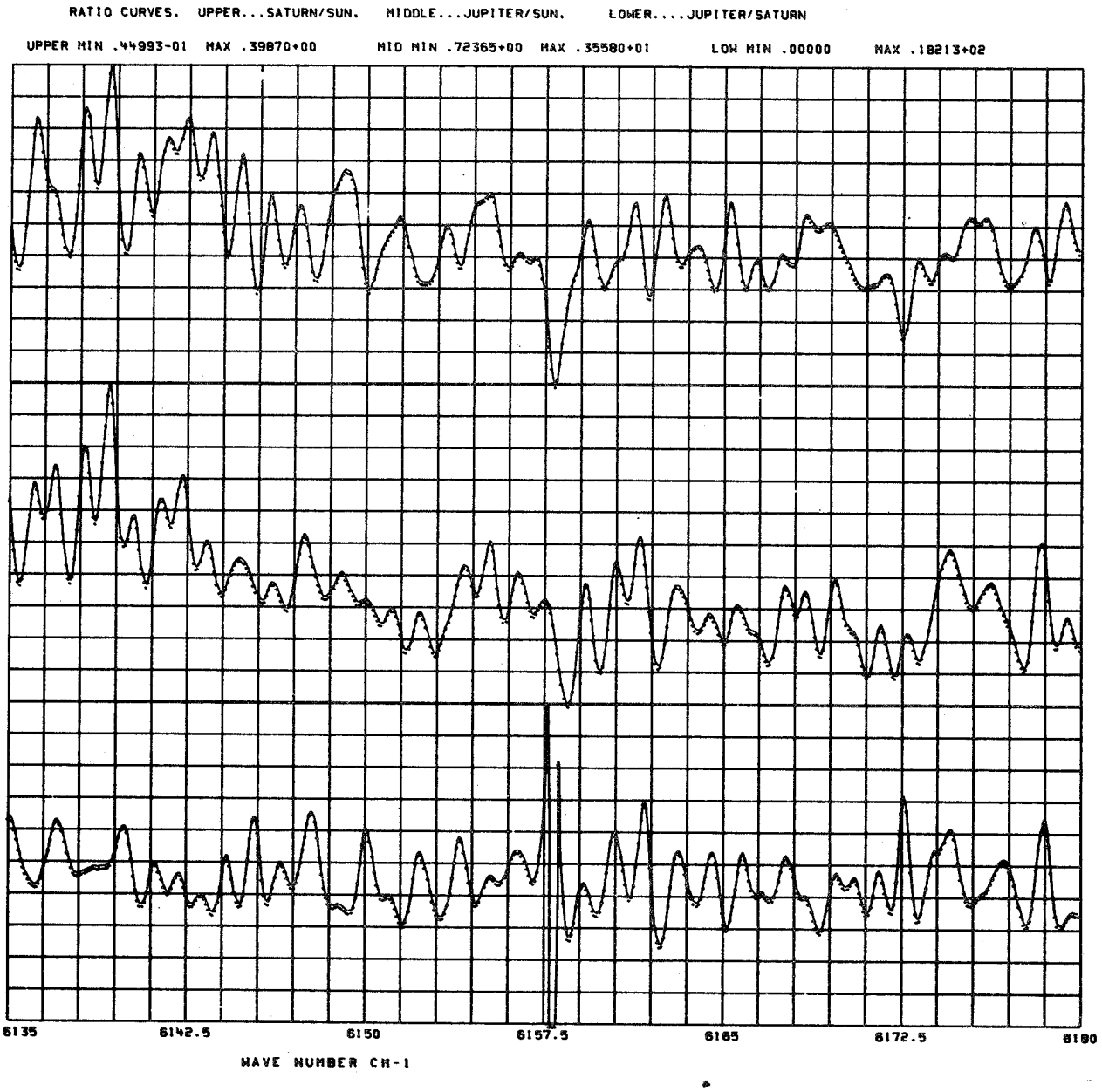
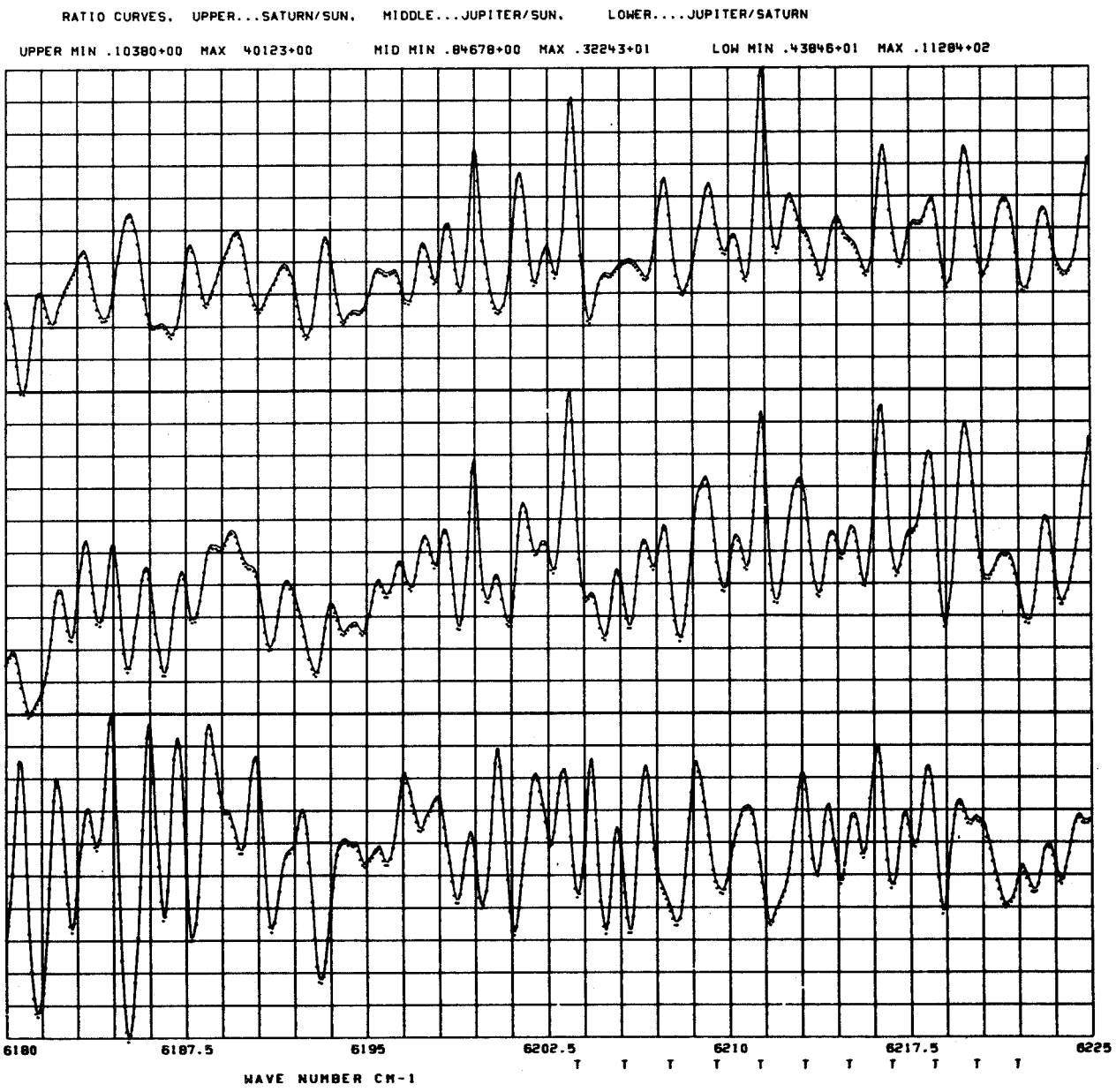


Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.



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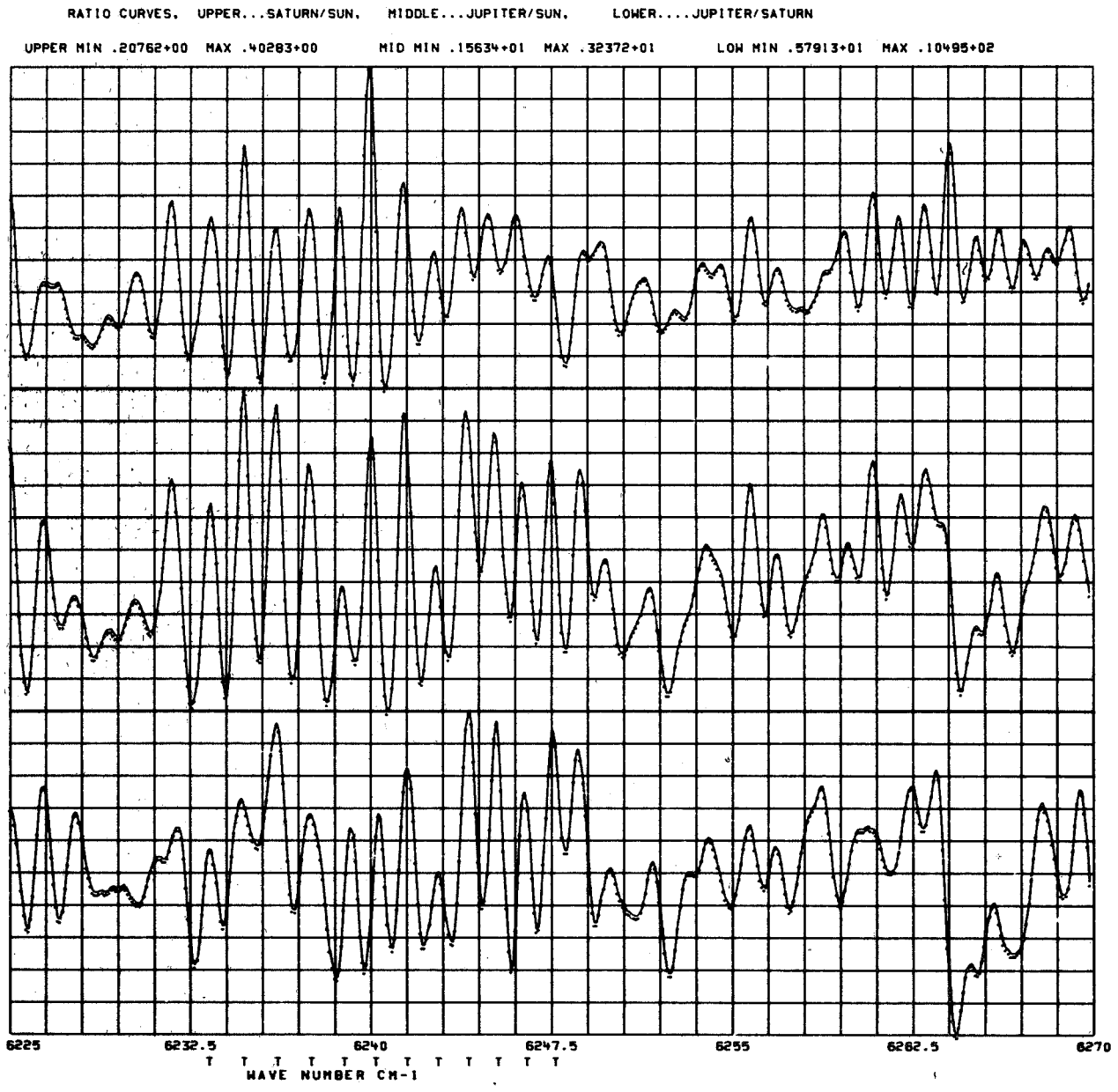

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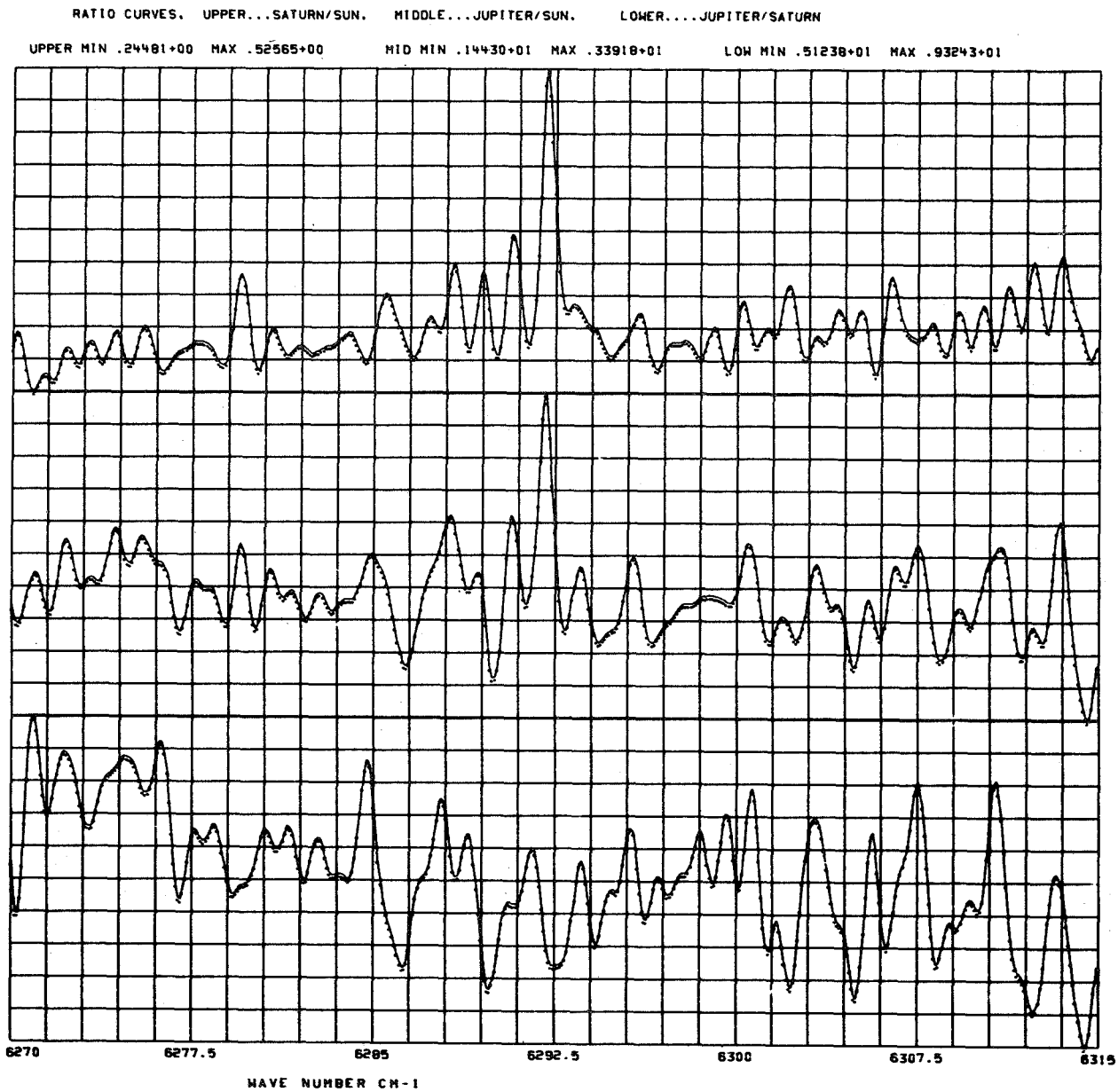

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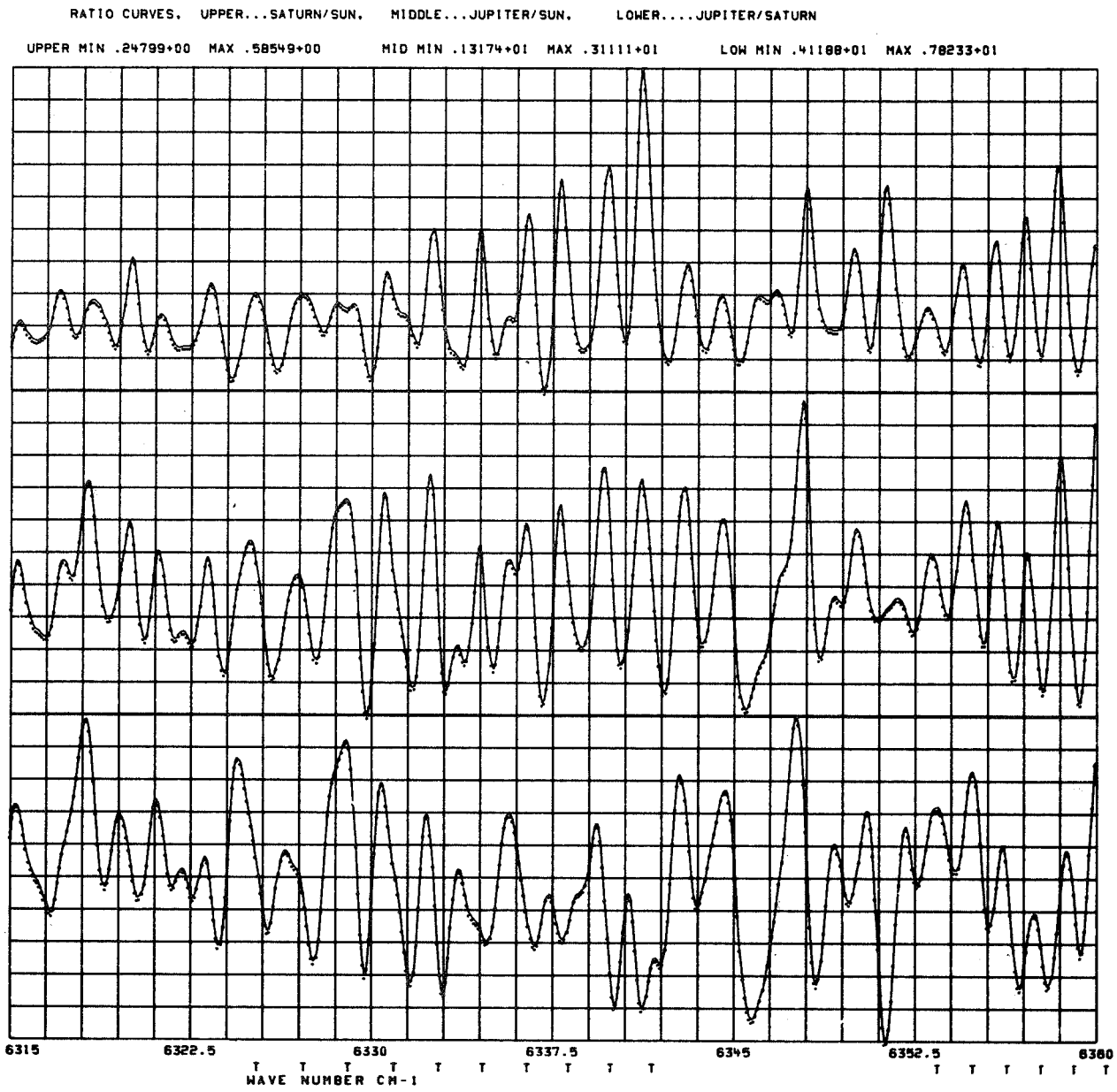

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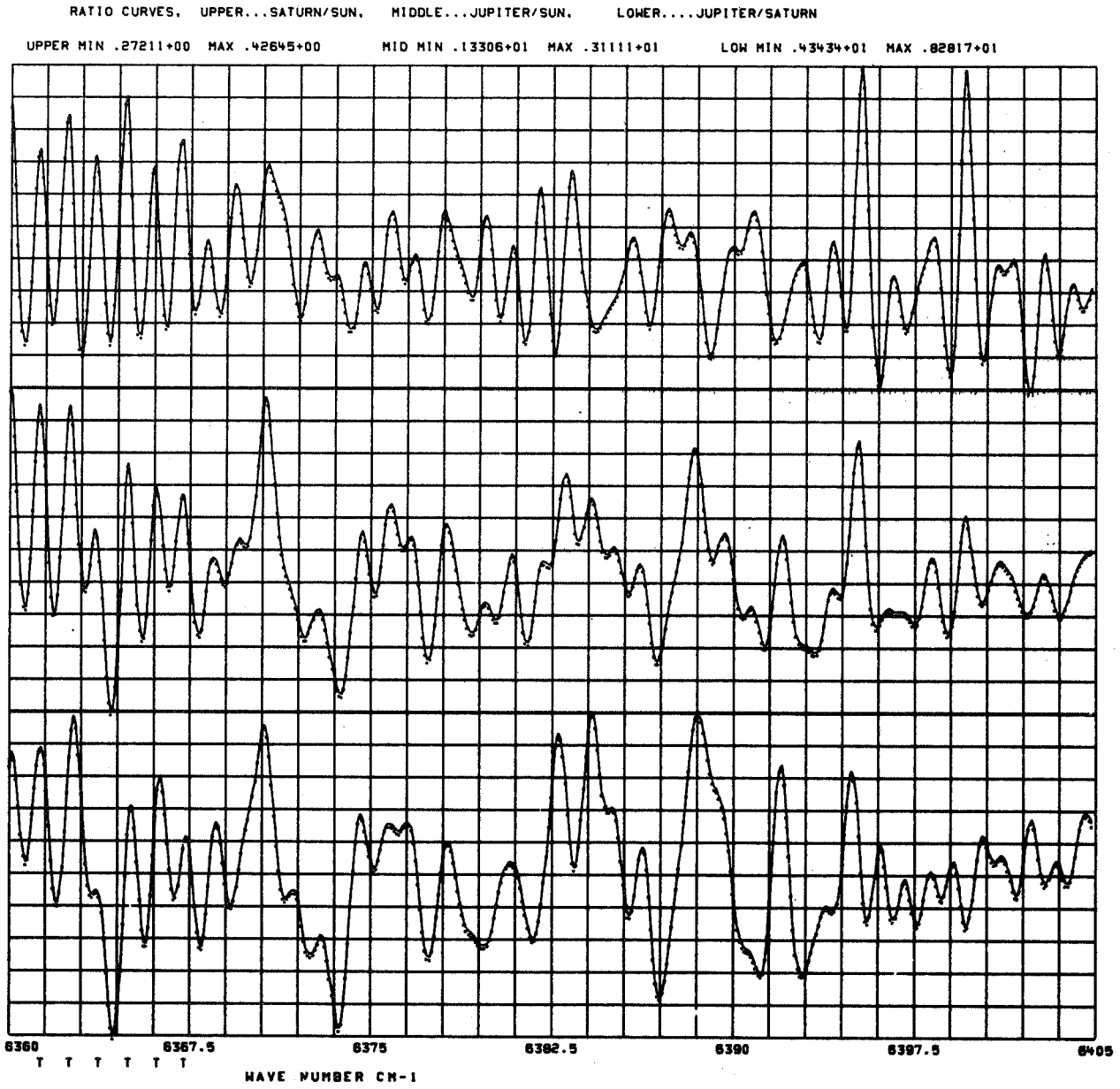

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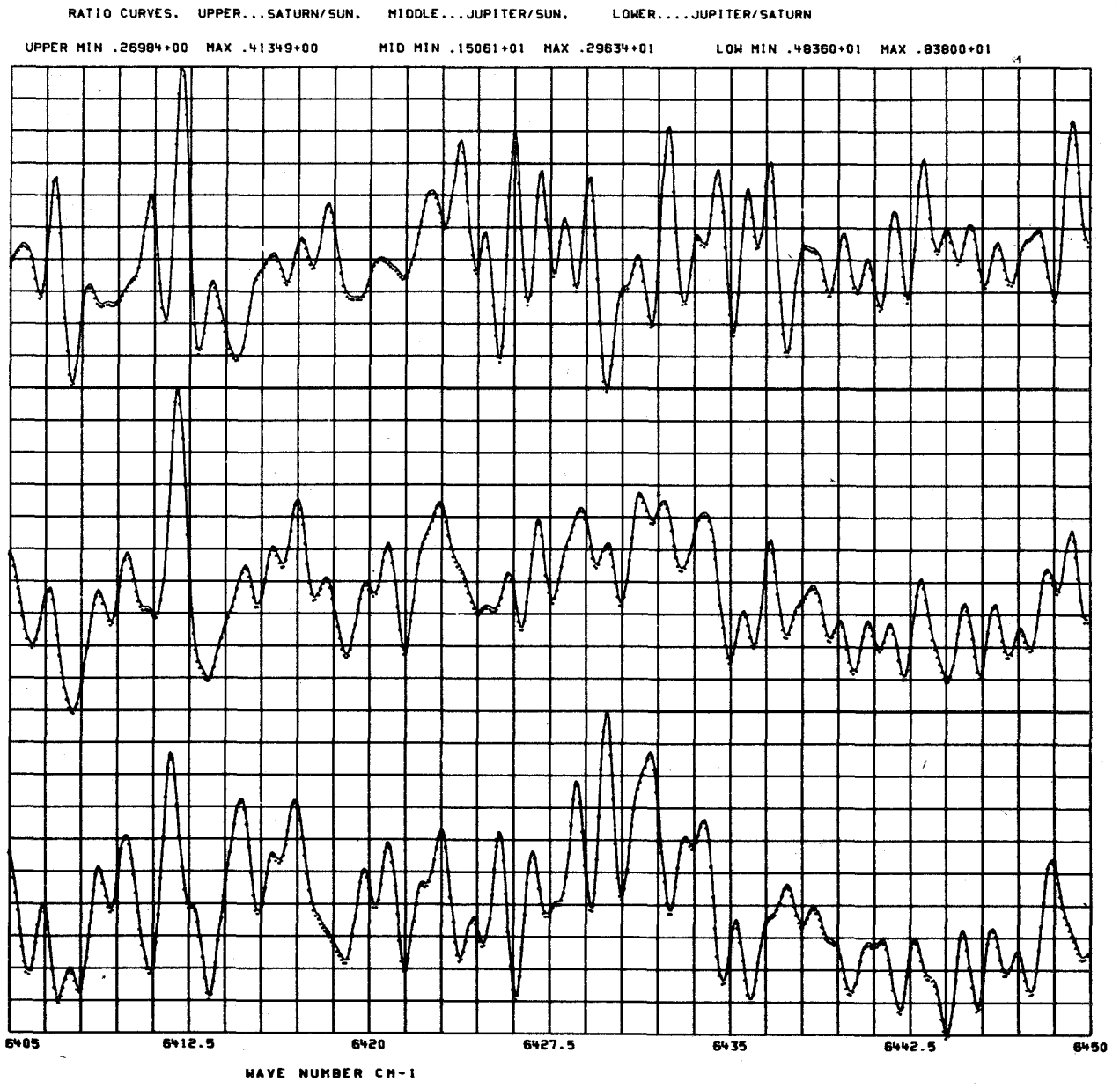

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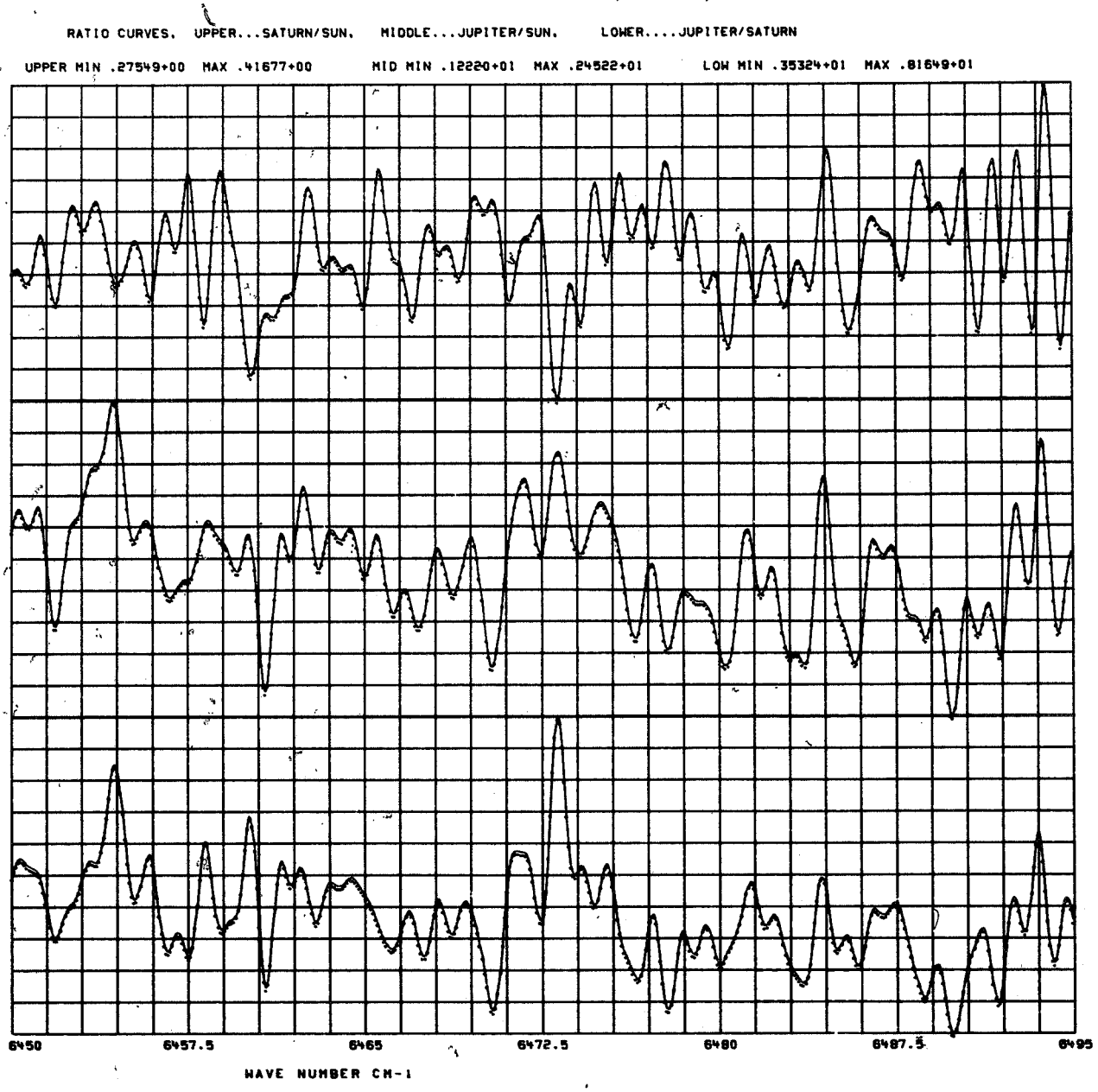

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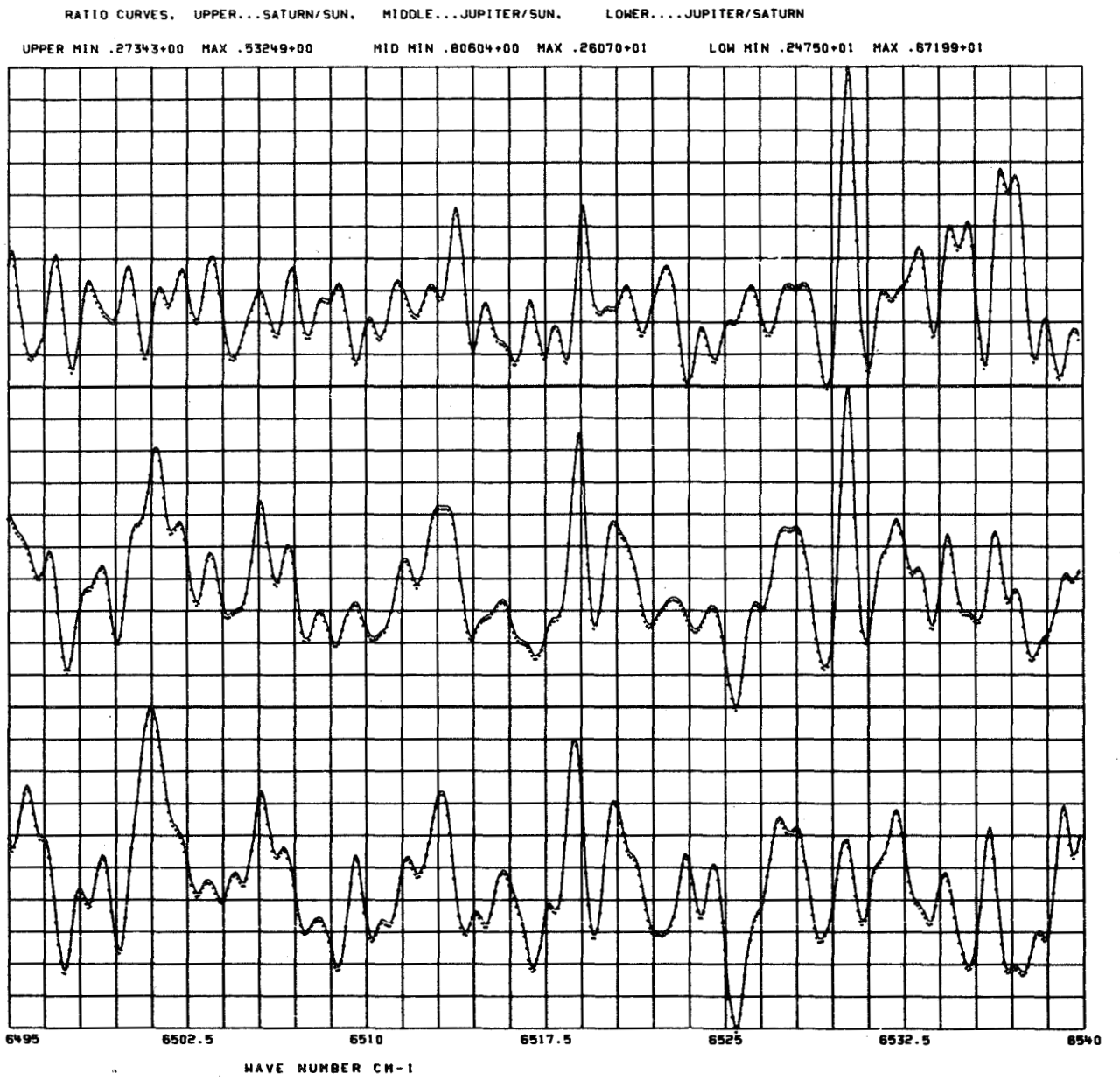

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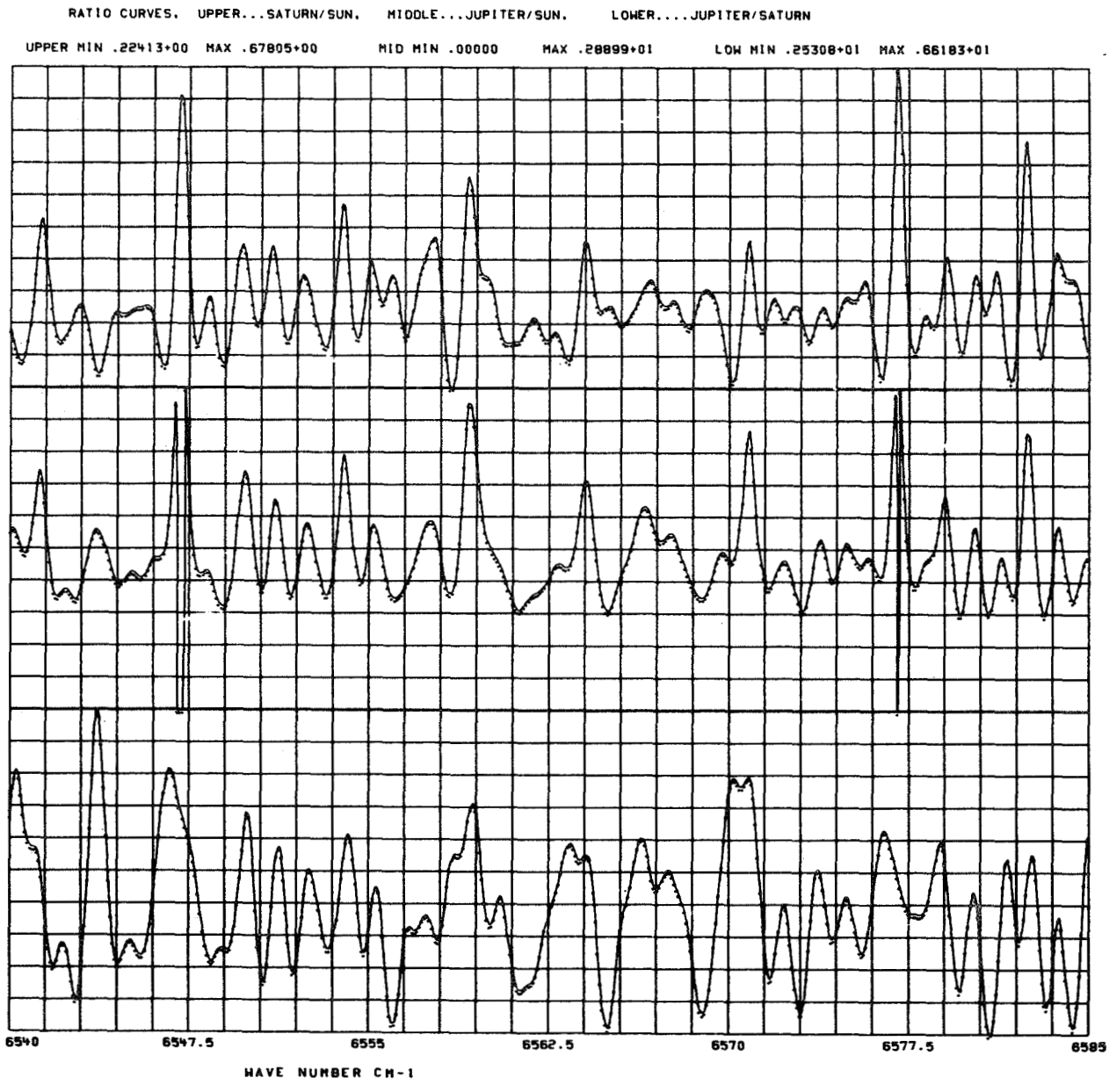

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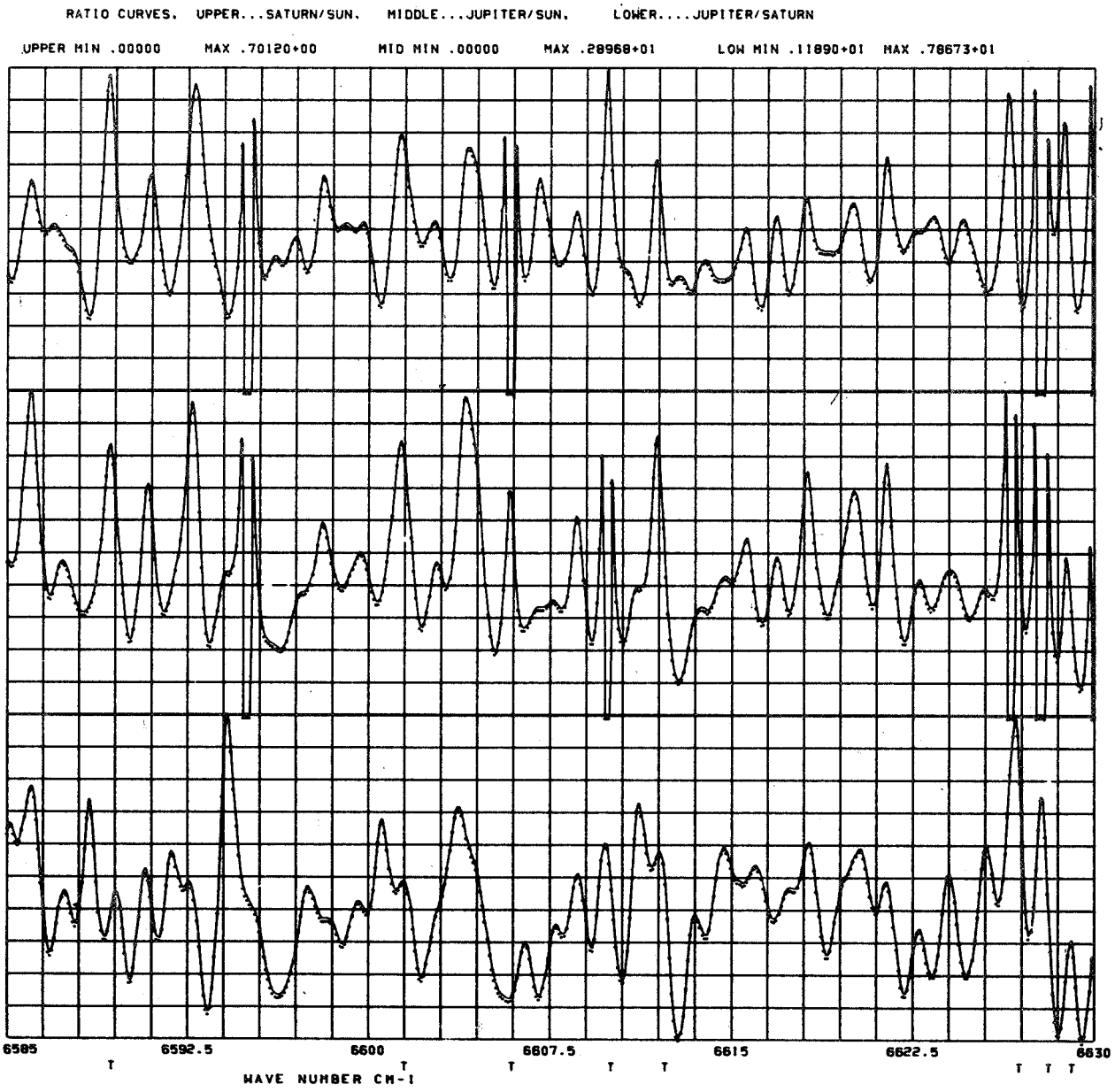

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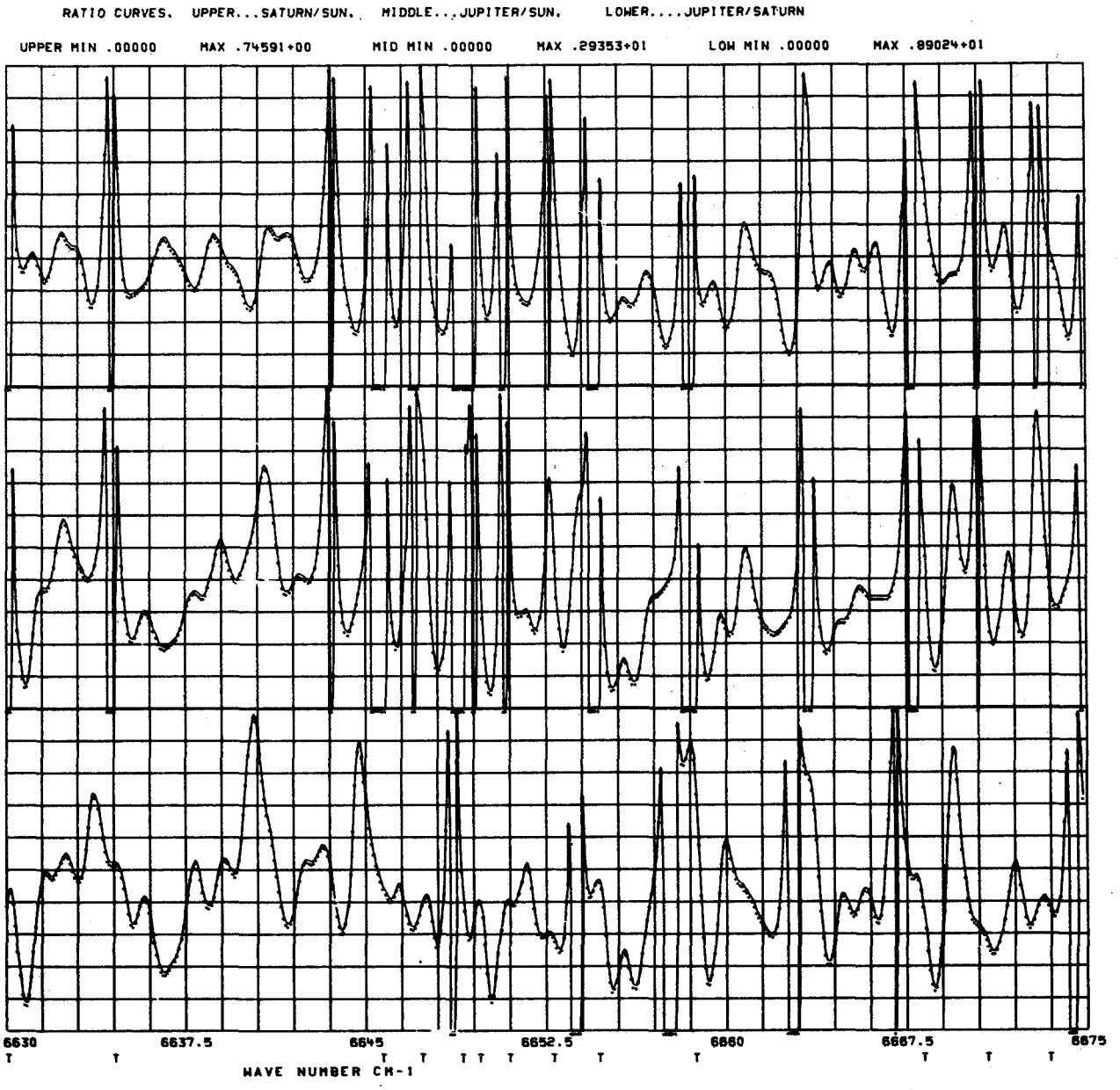

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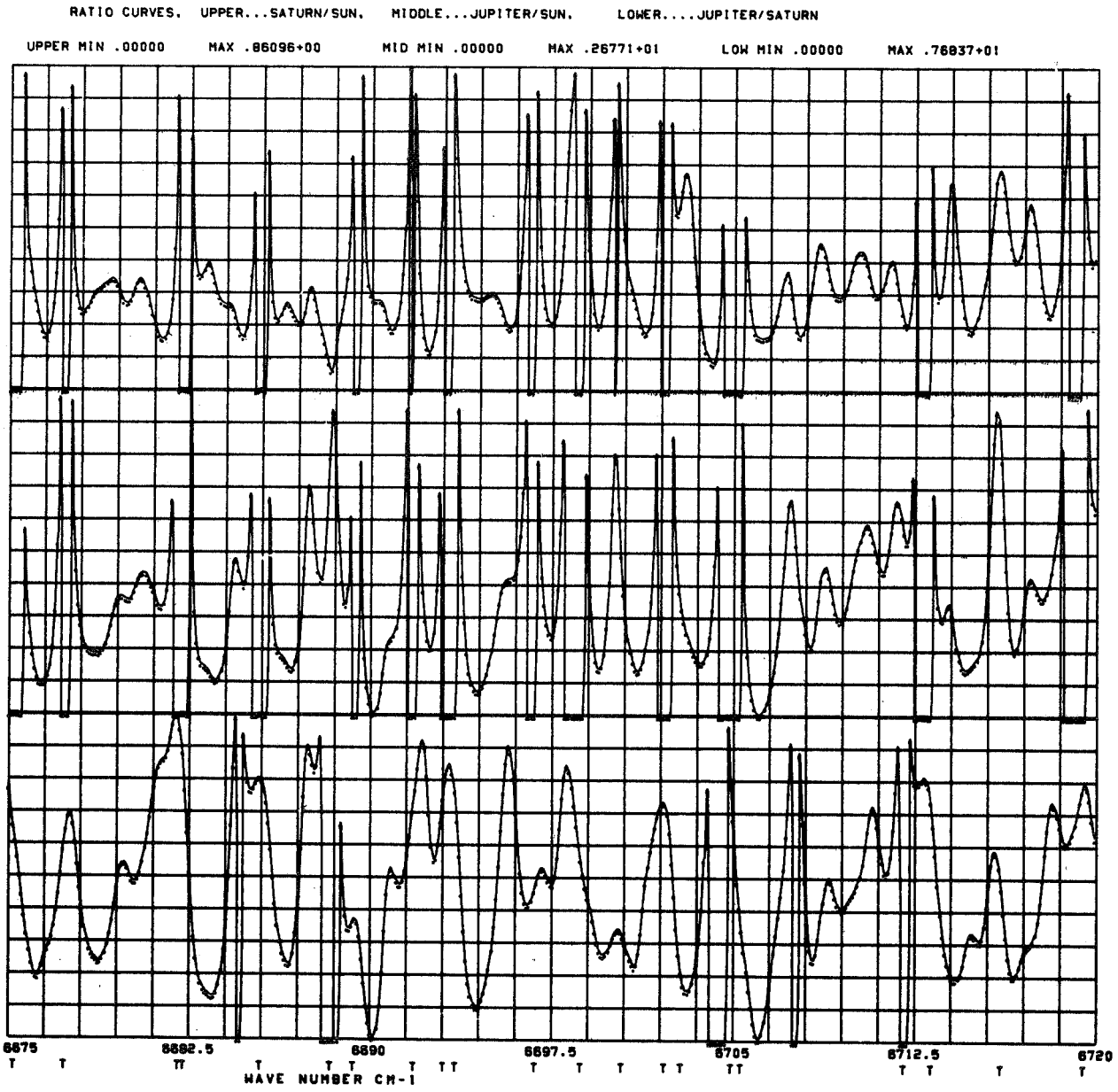

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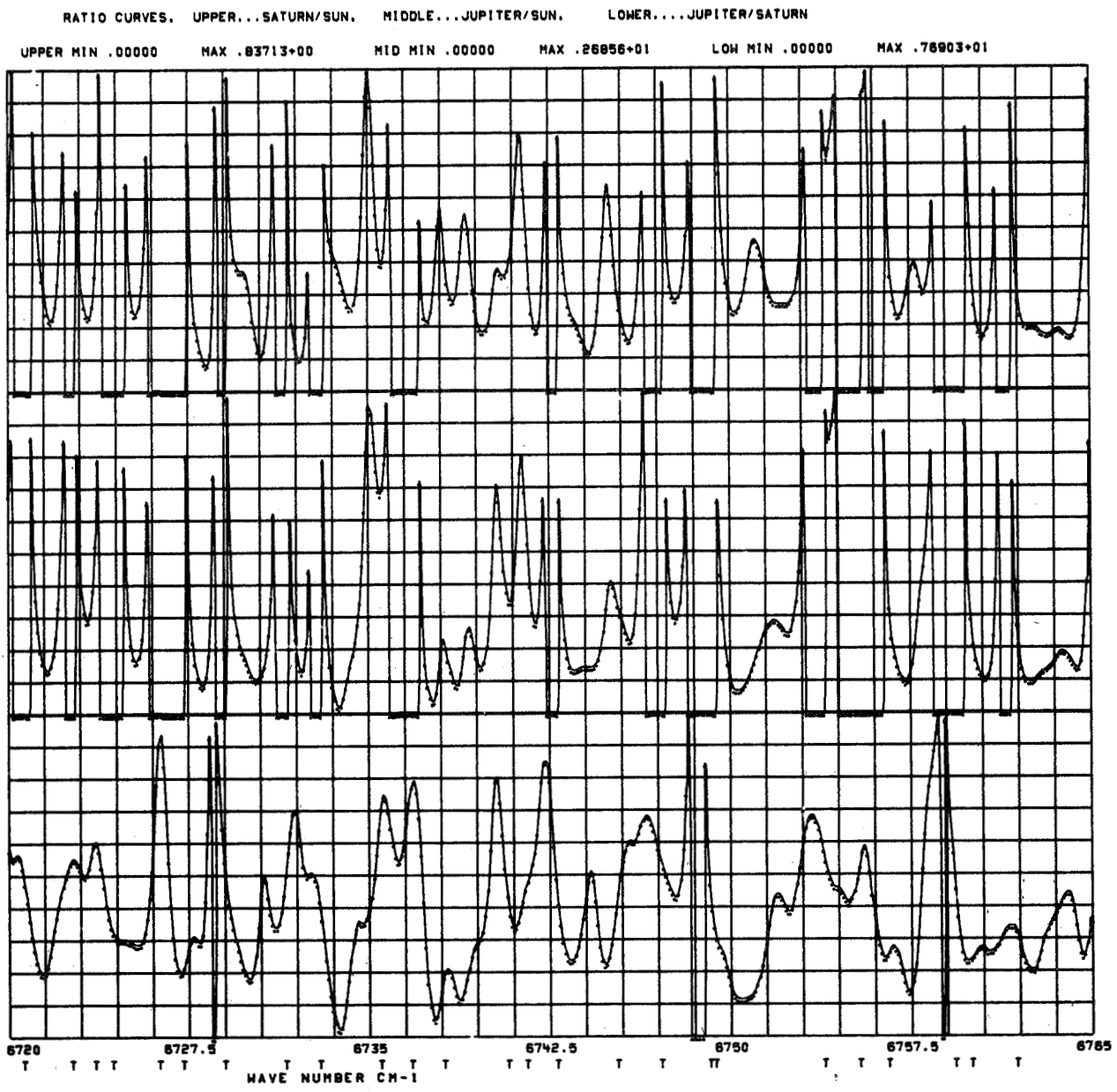

Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

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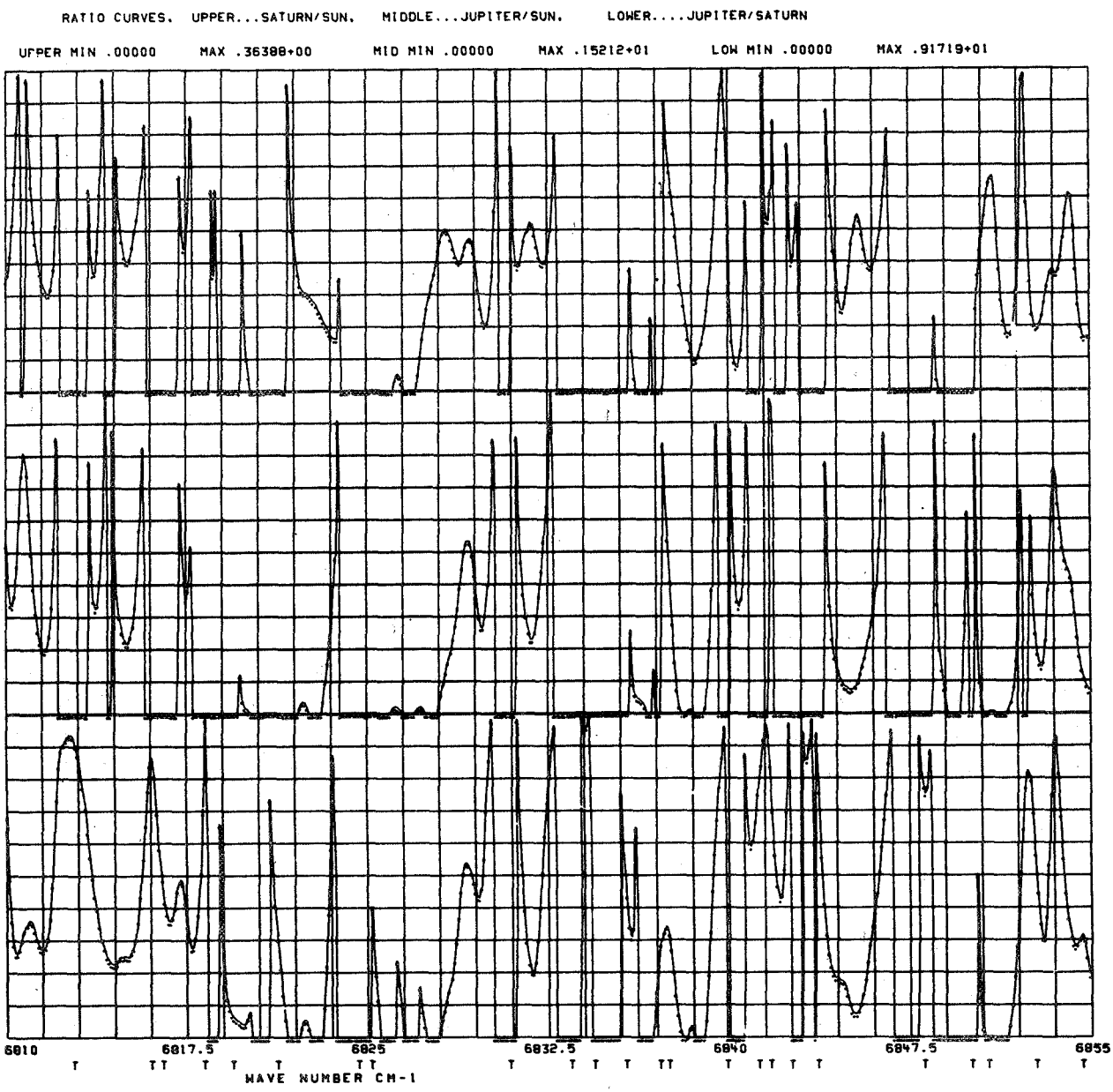

Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}

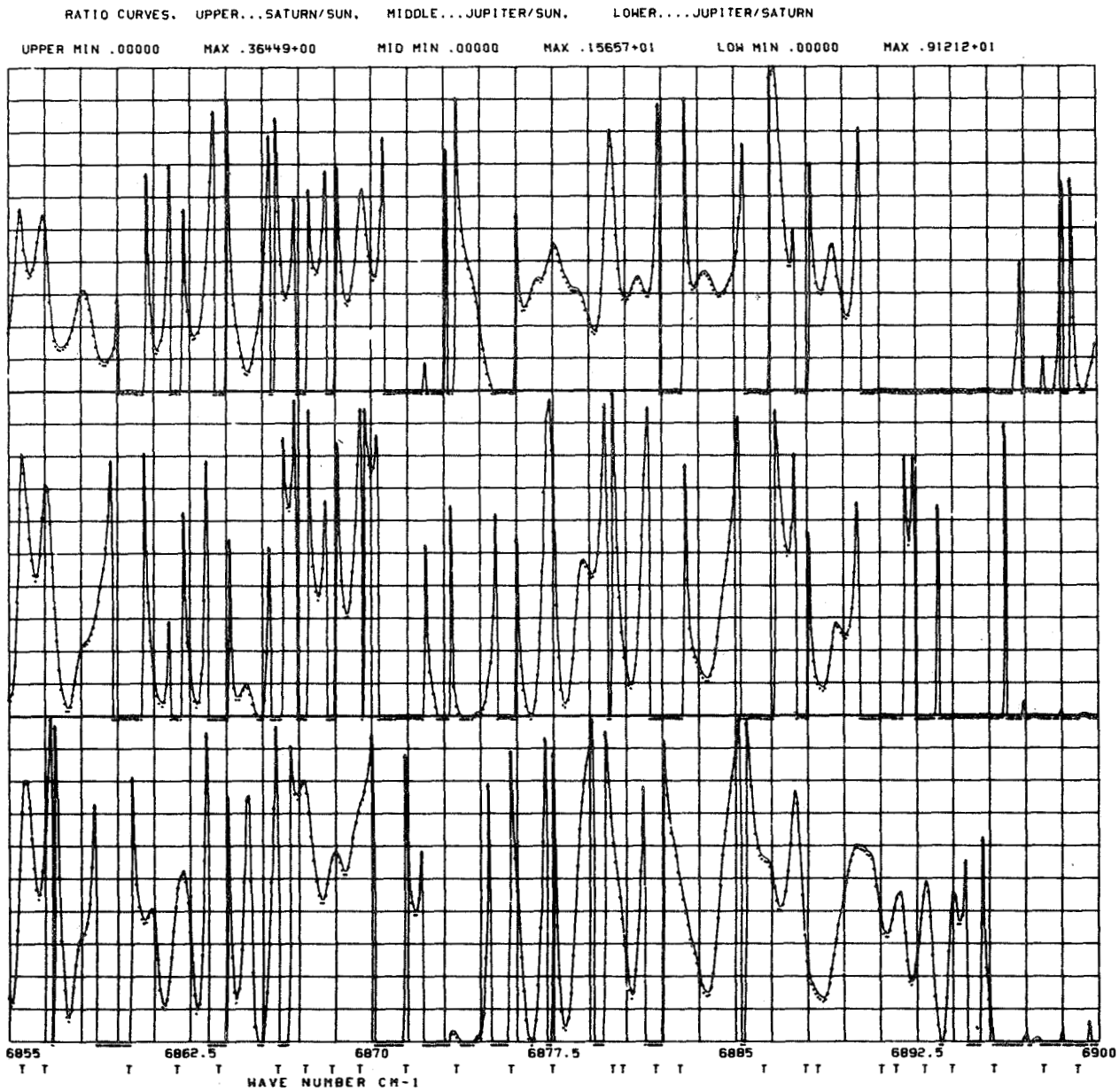

Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

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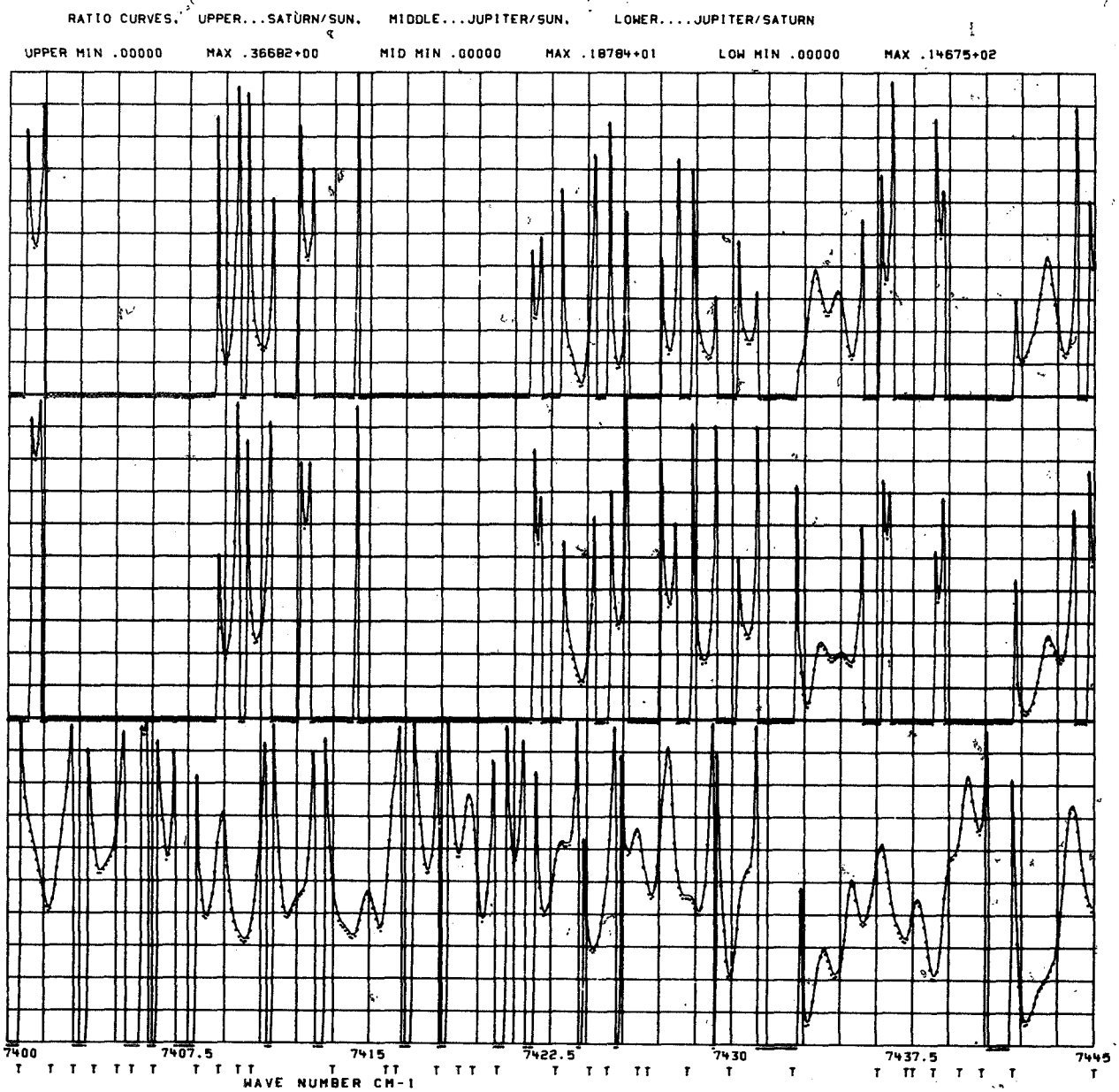

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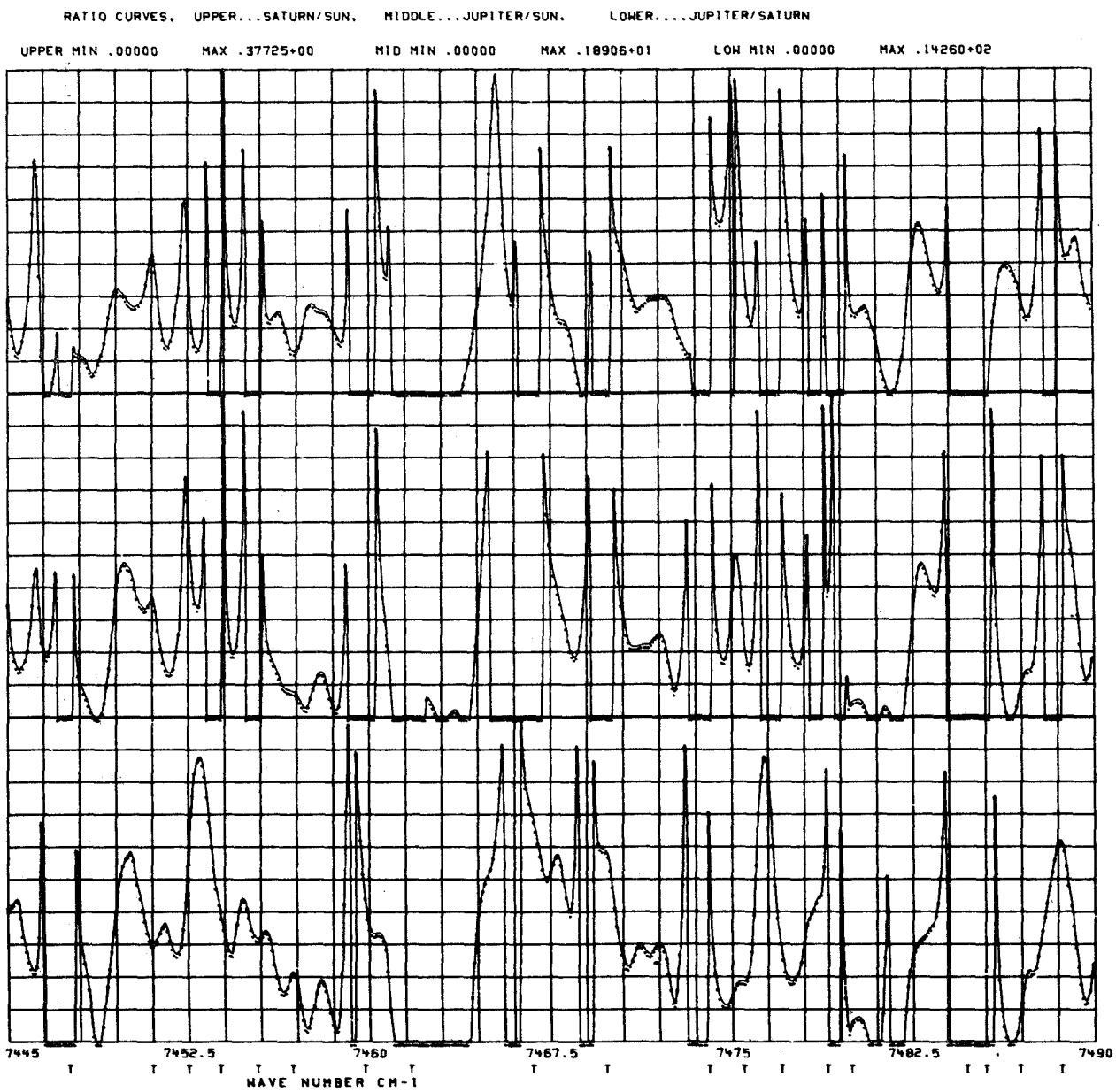

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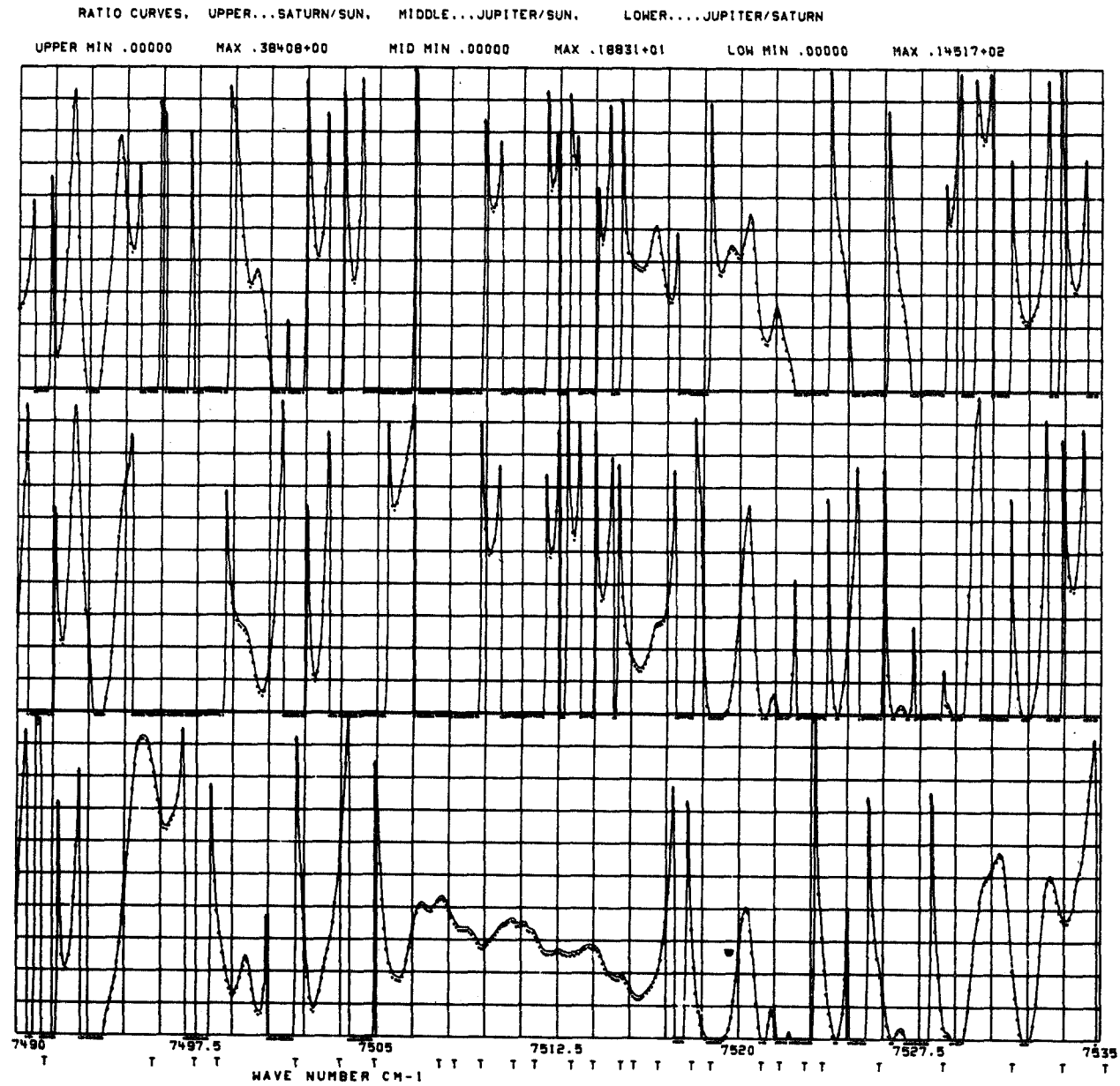

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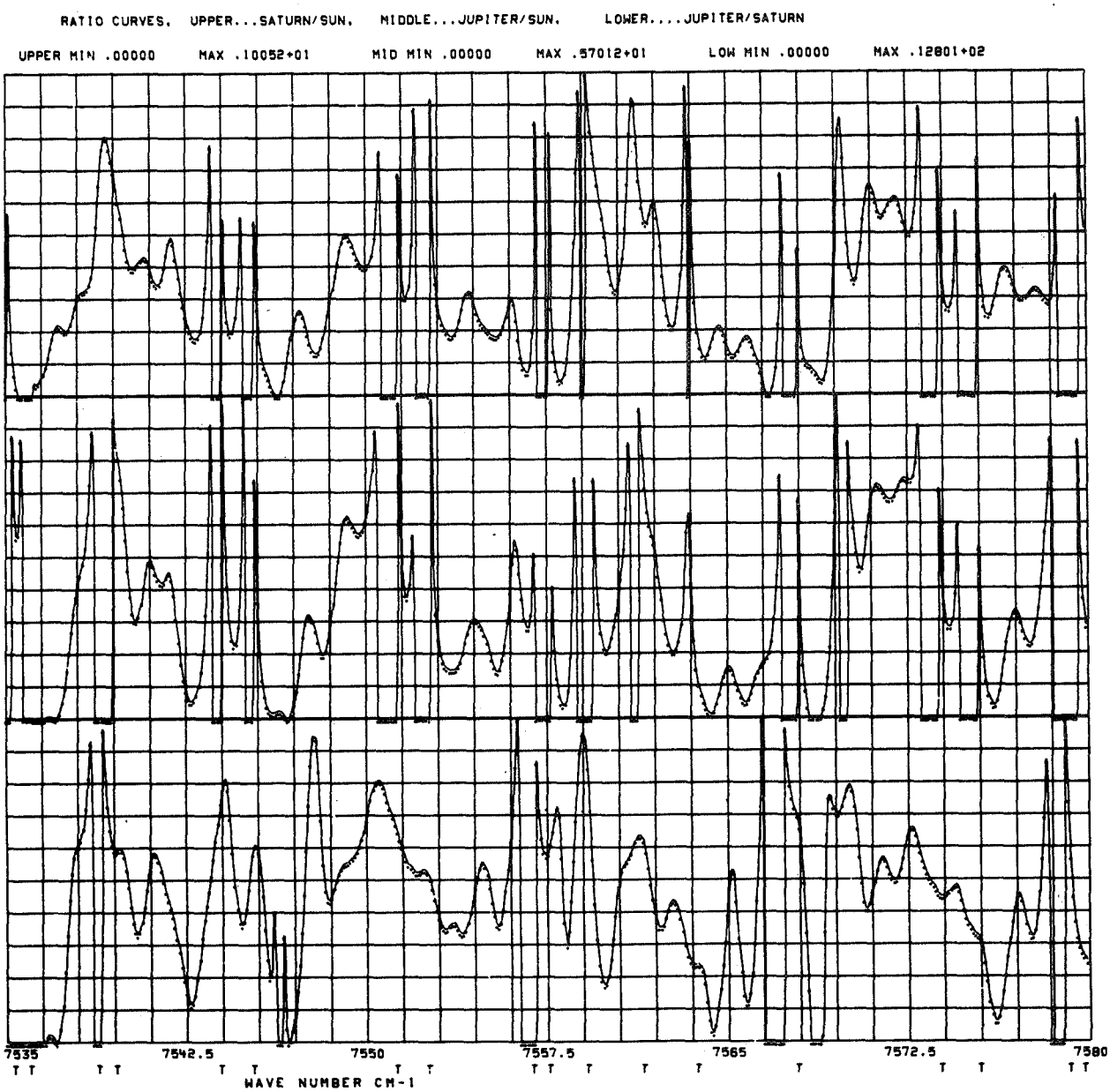

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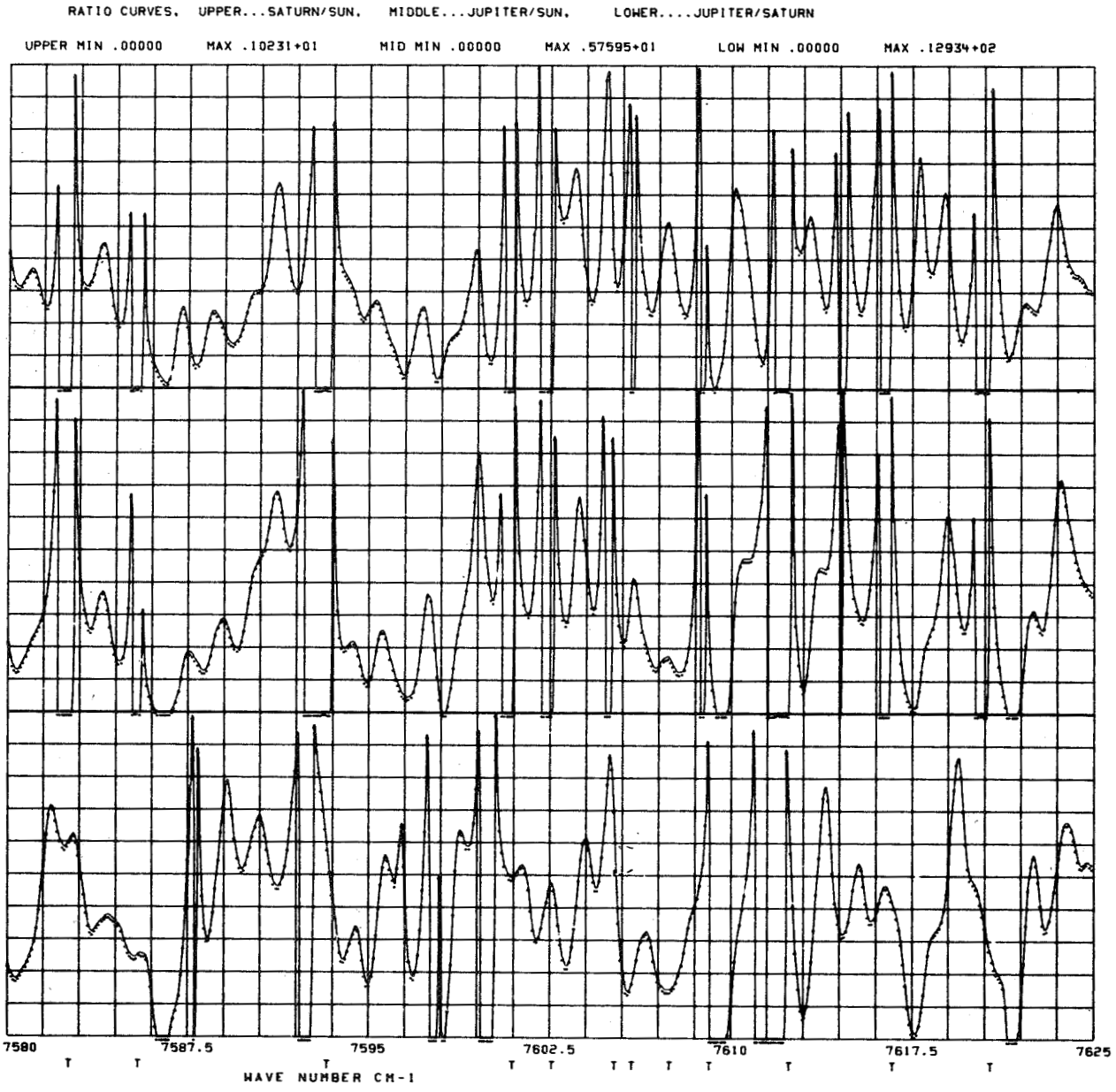

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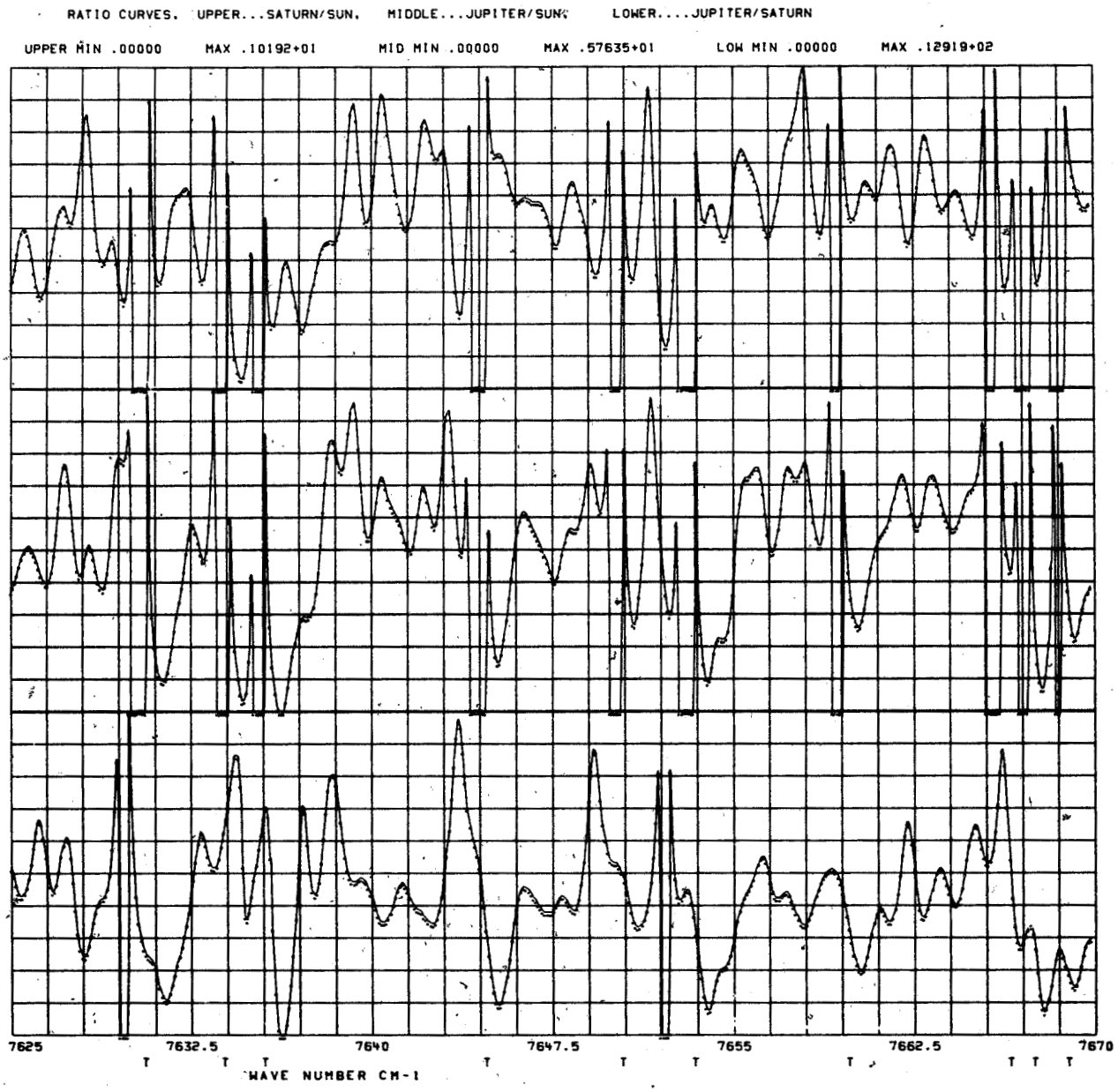

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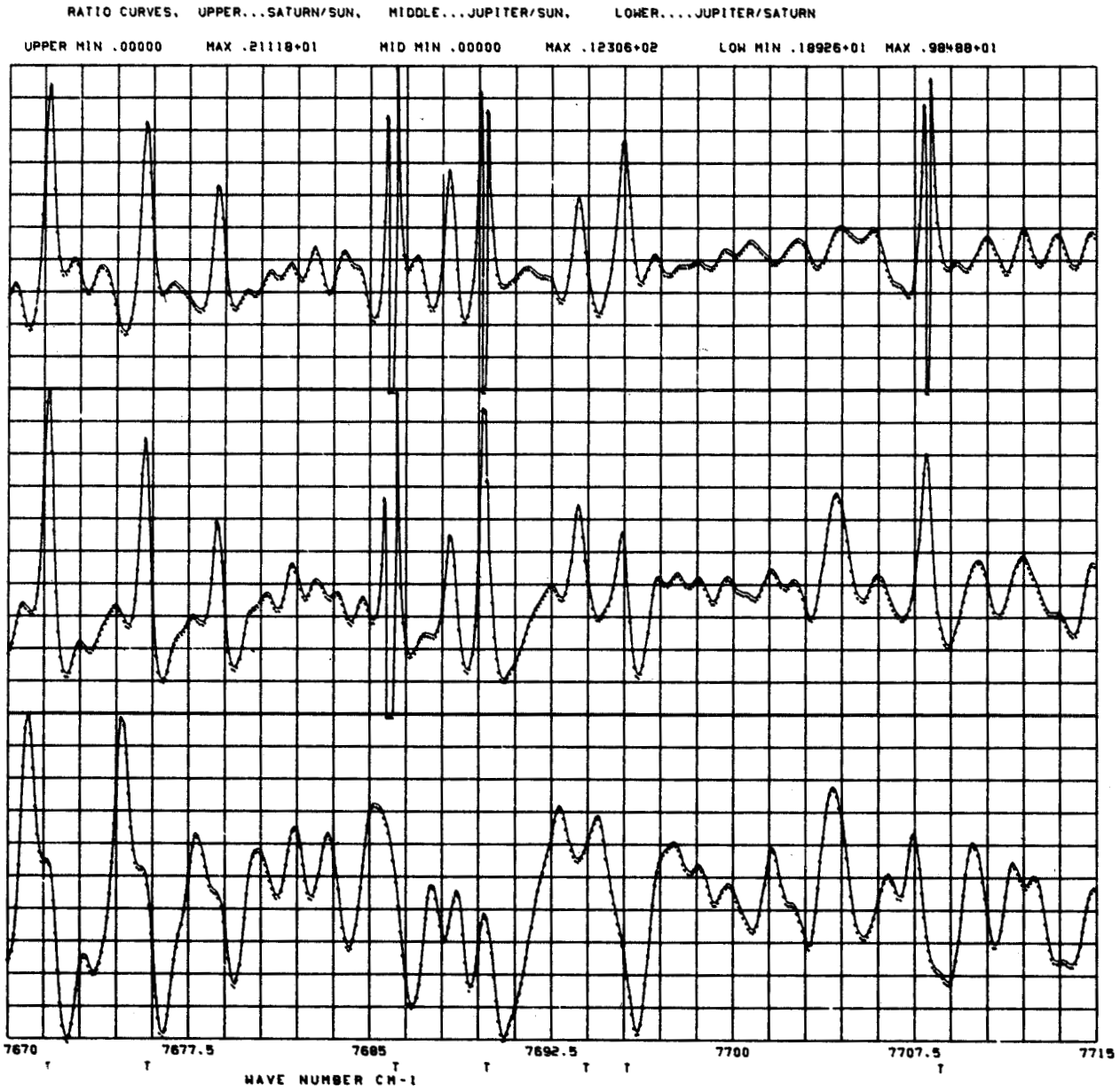

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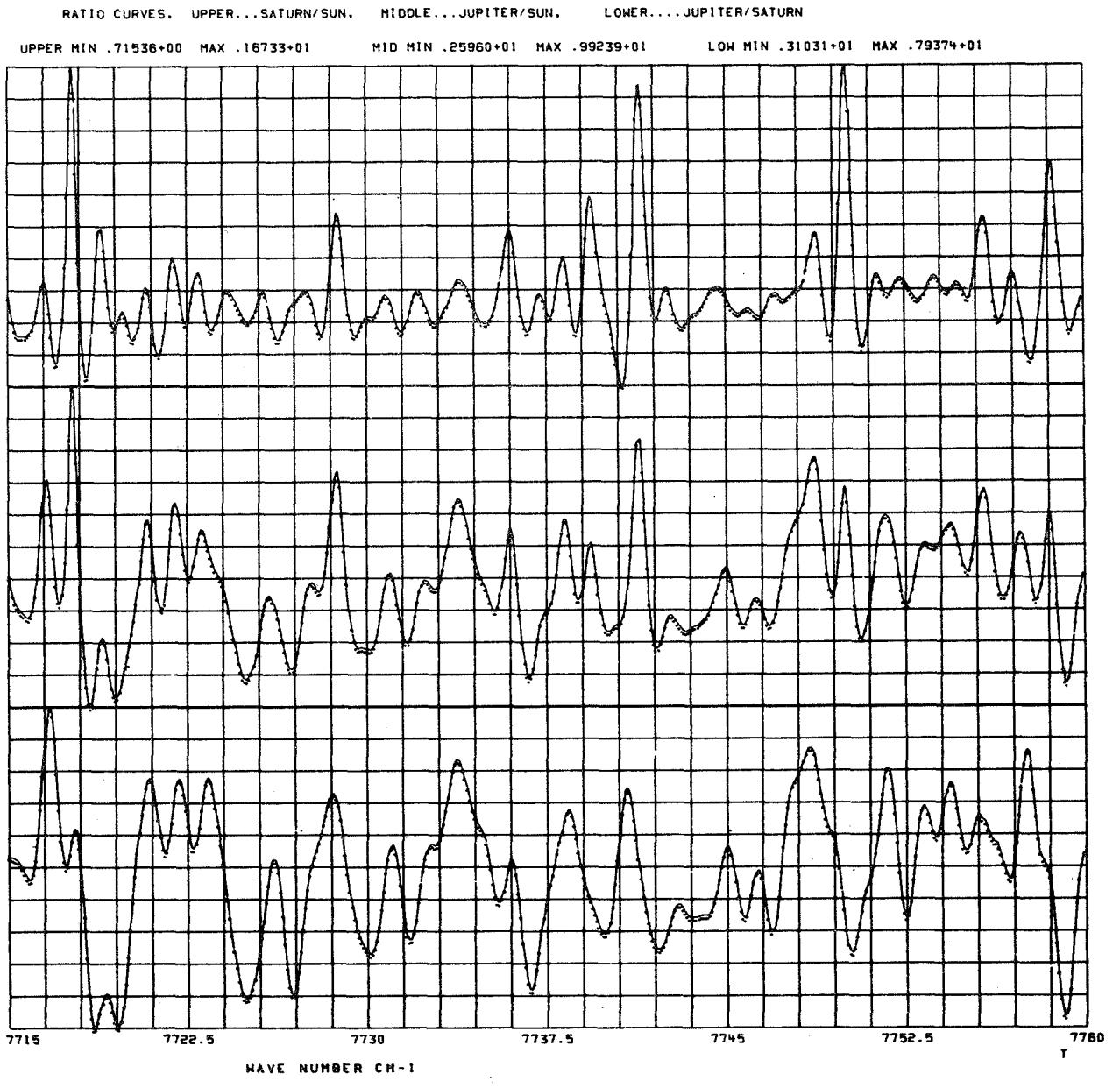

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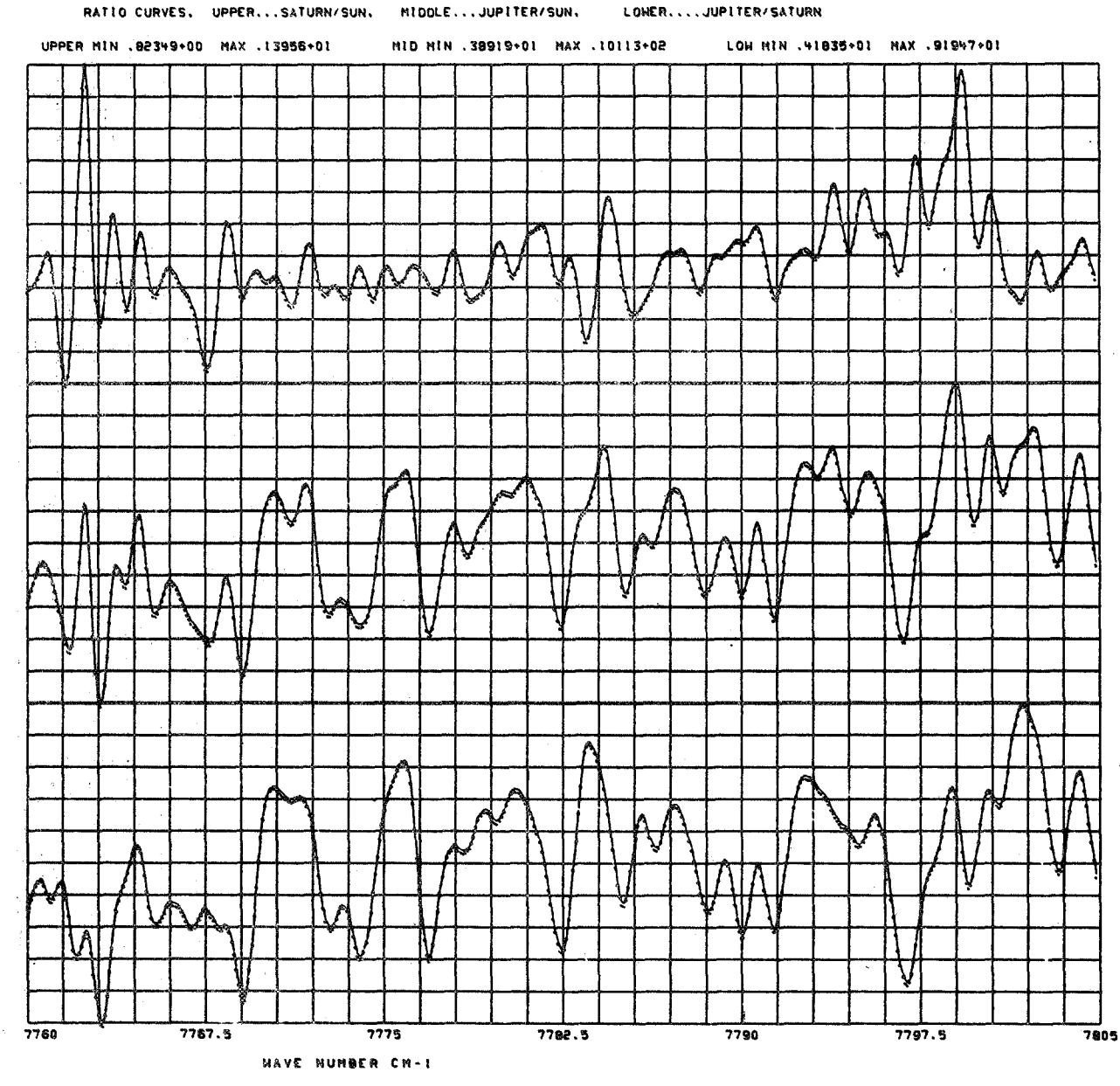

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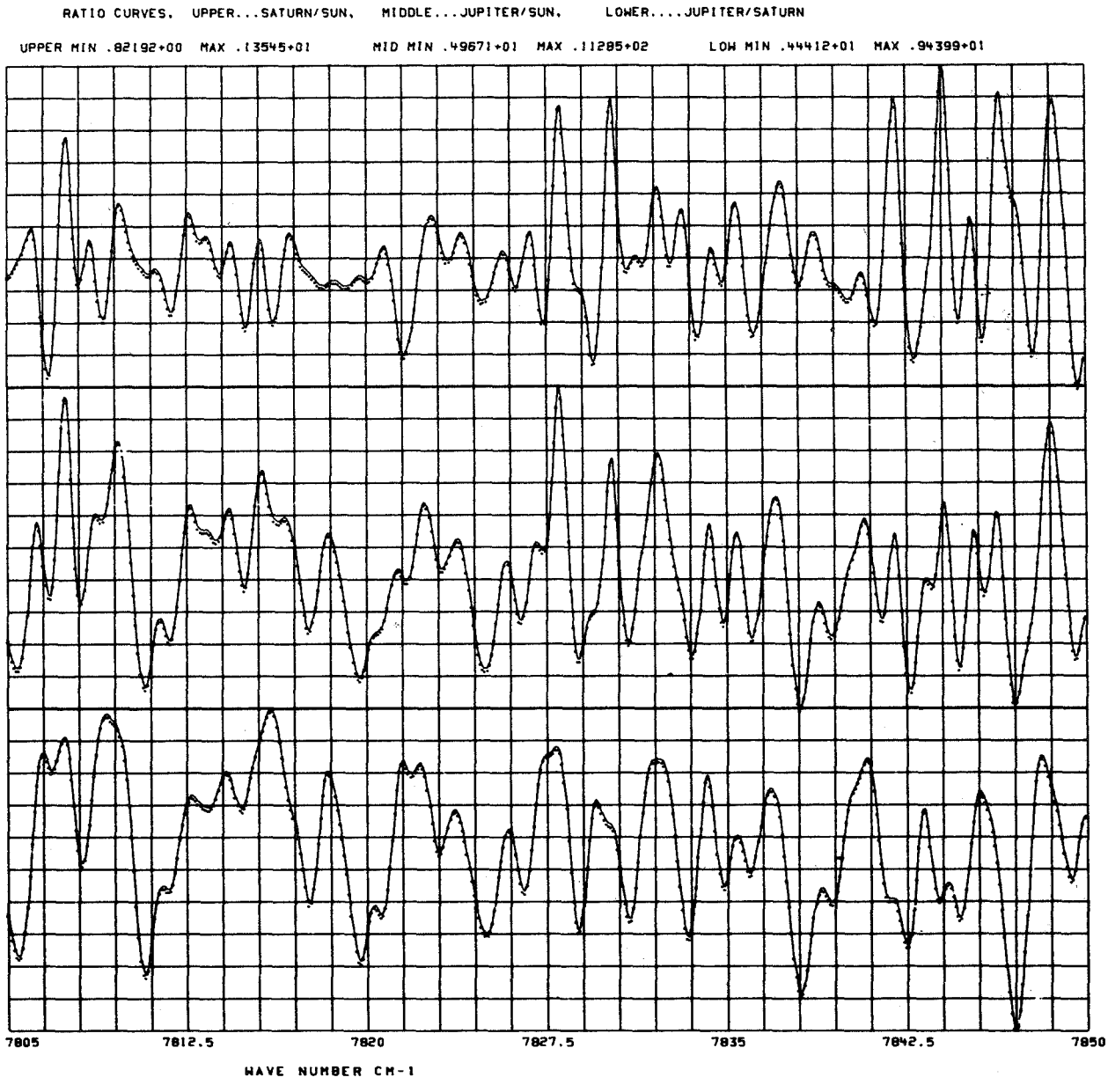

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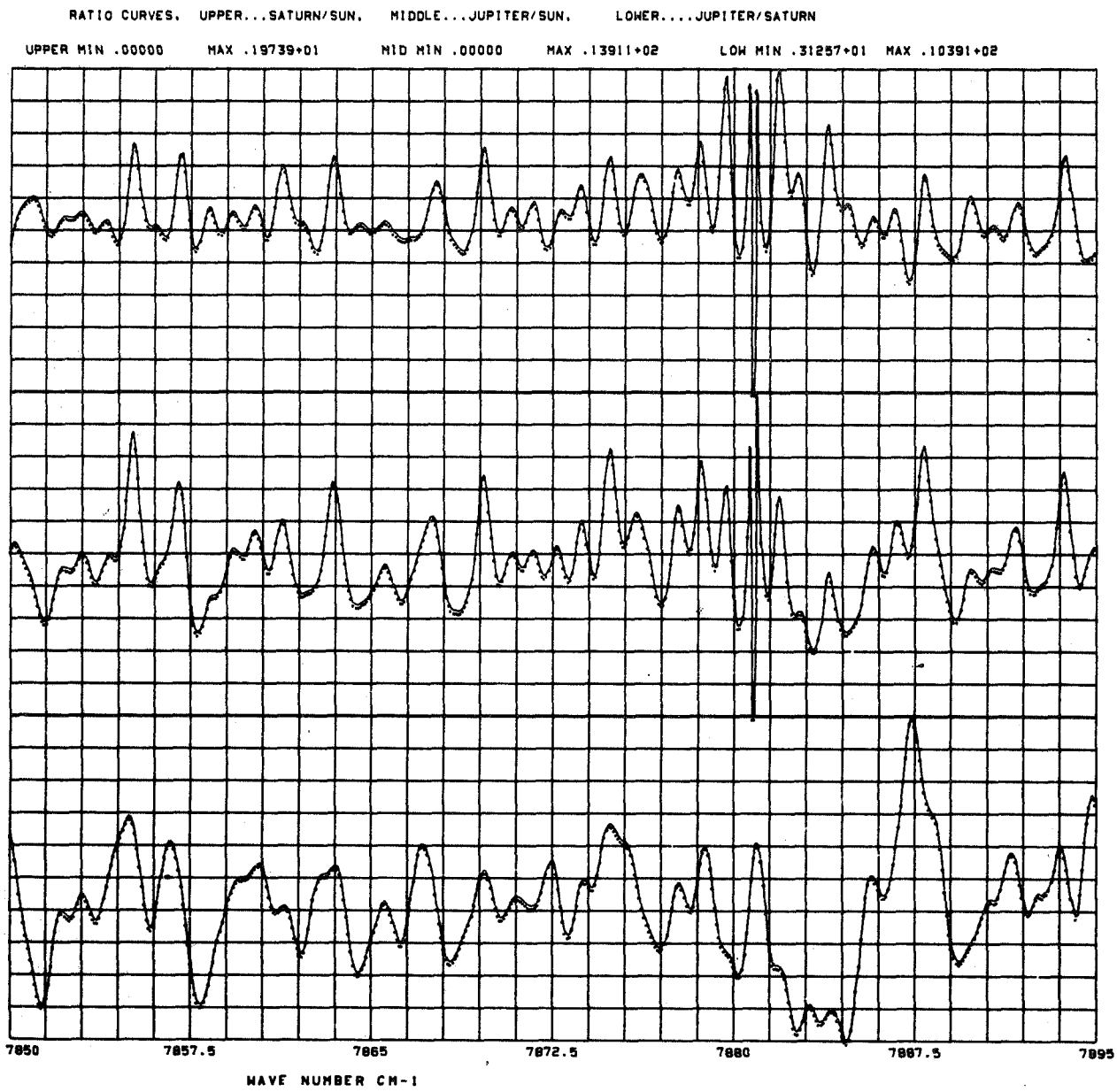

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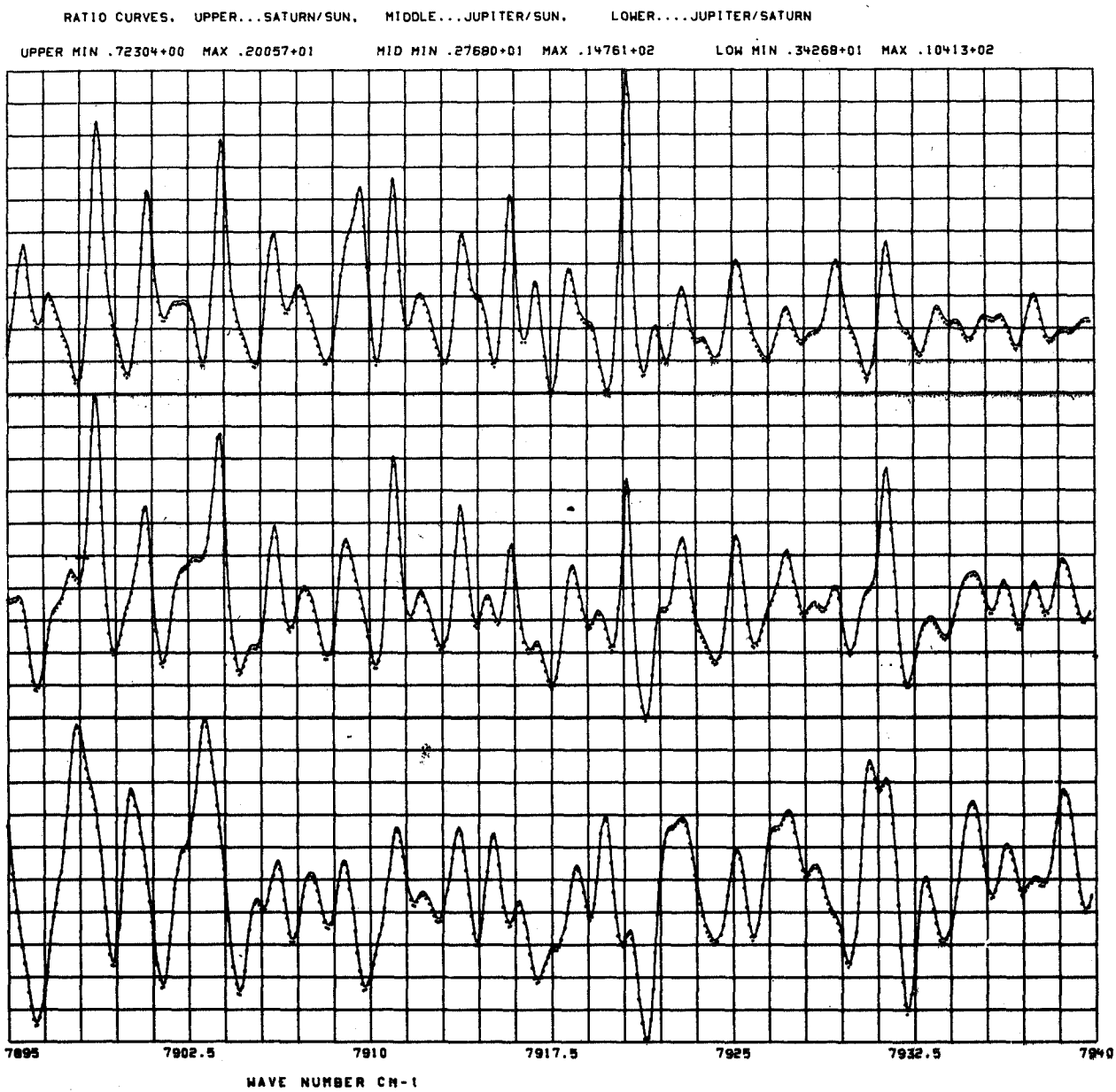

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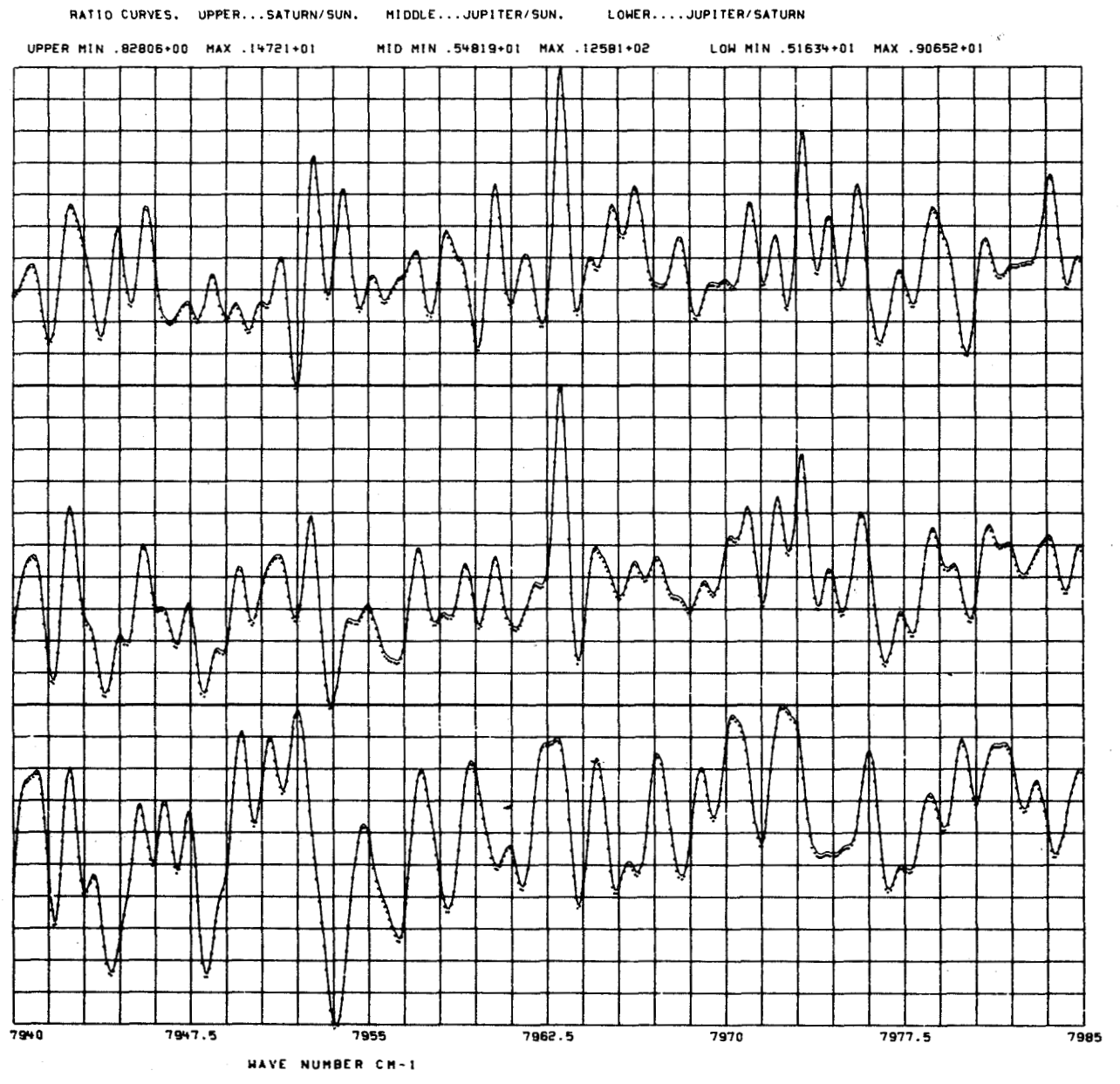

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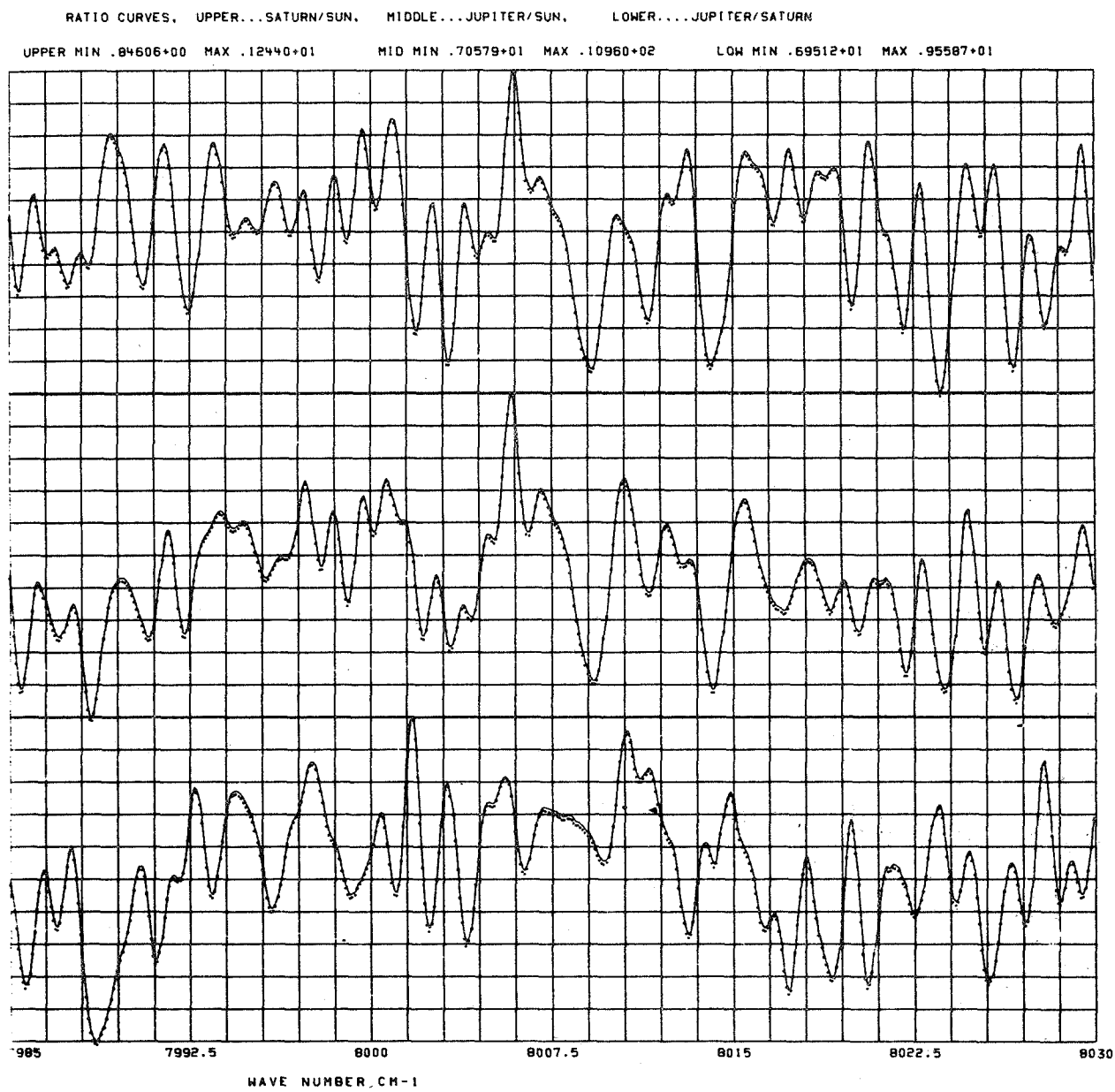

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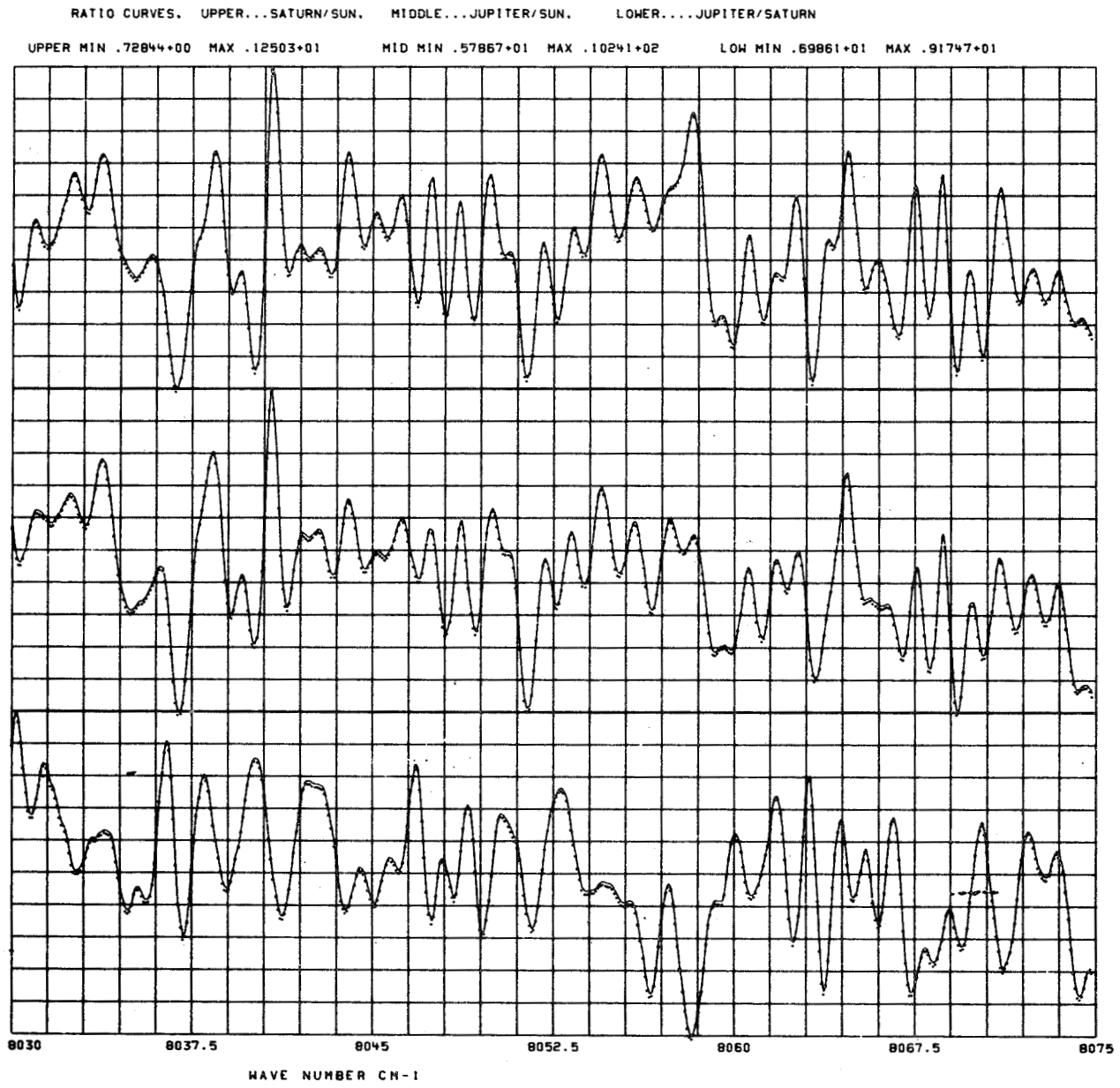

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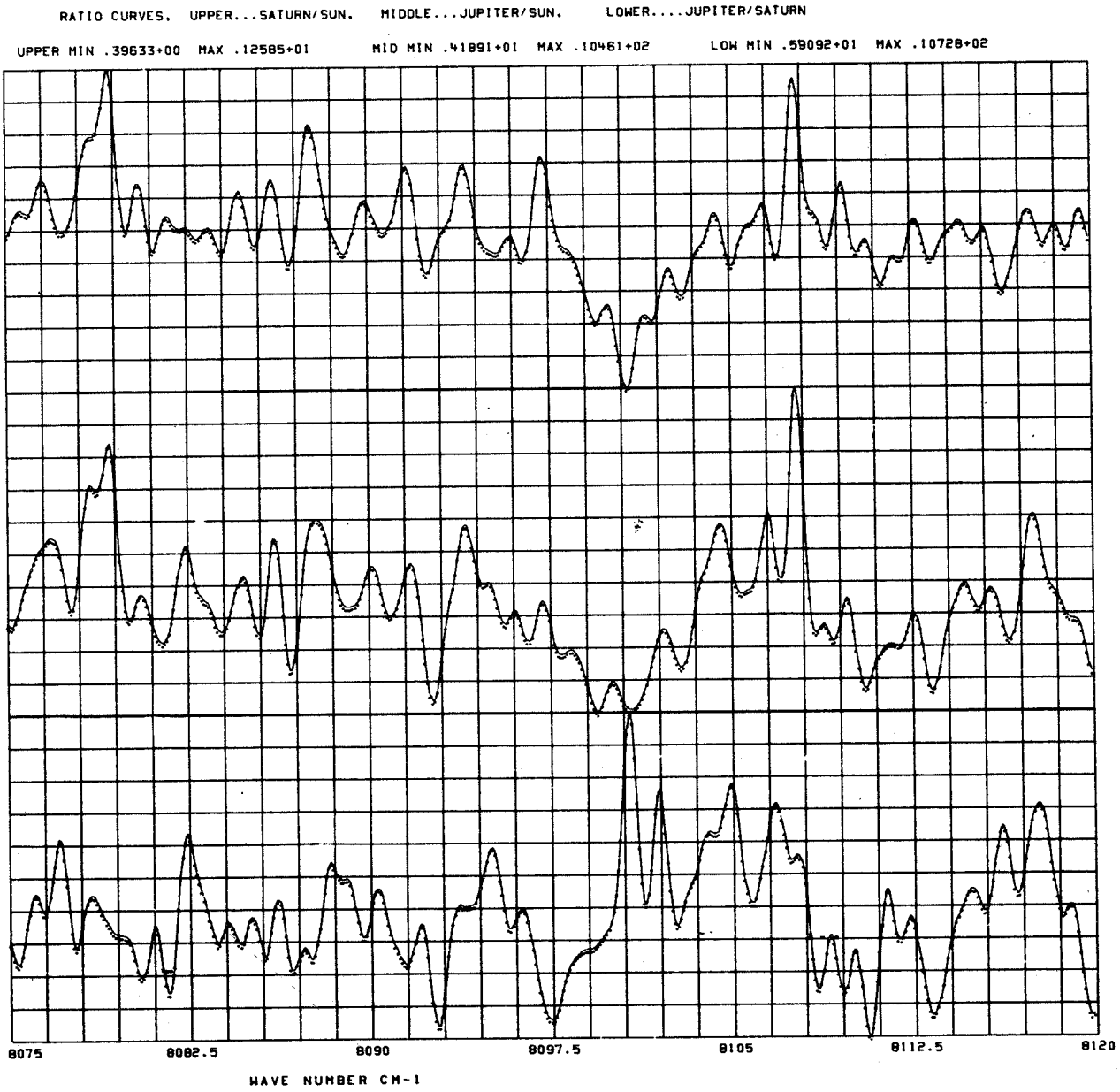


Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

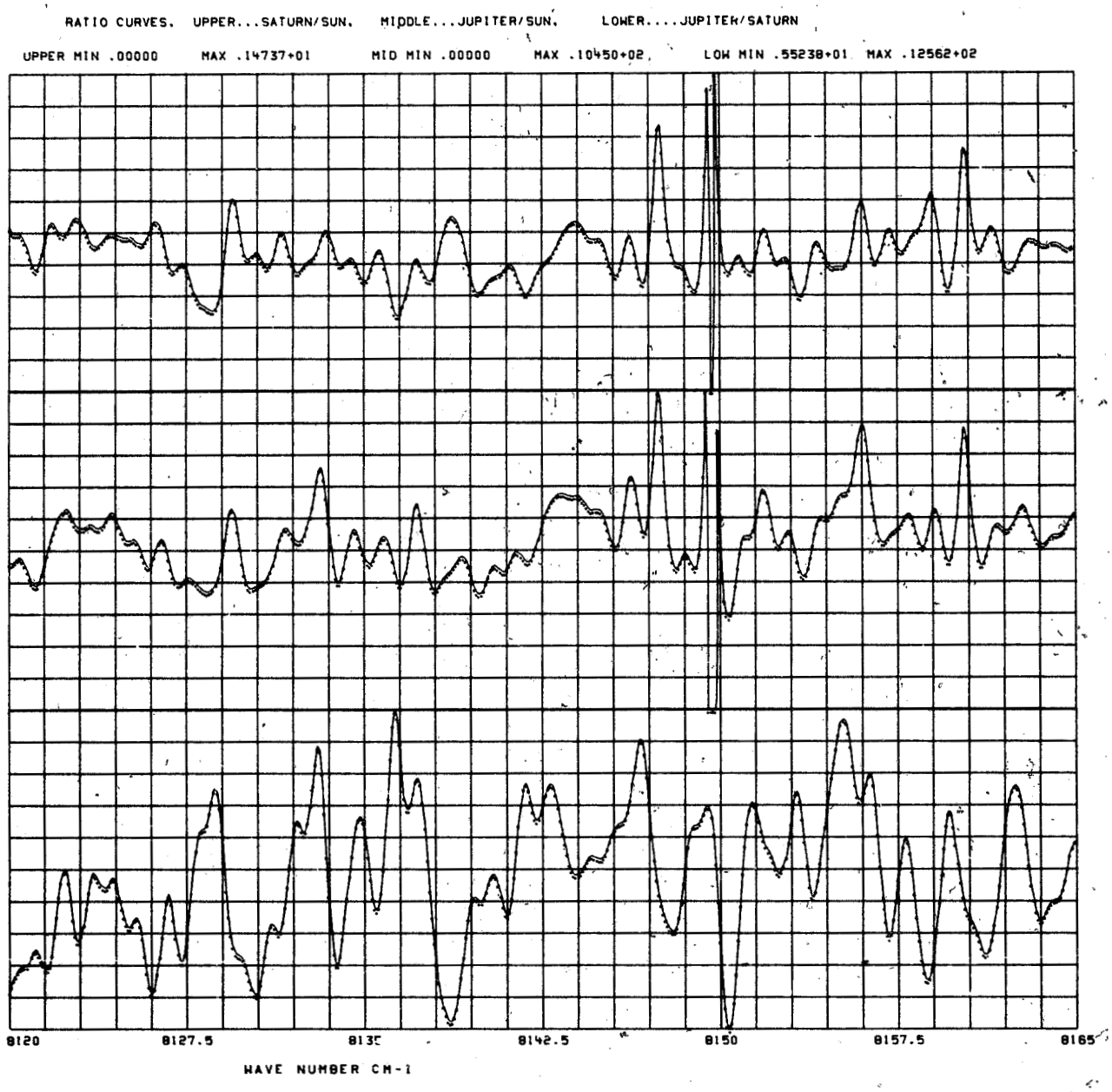


Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

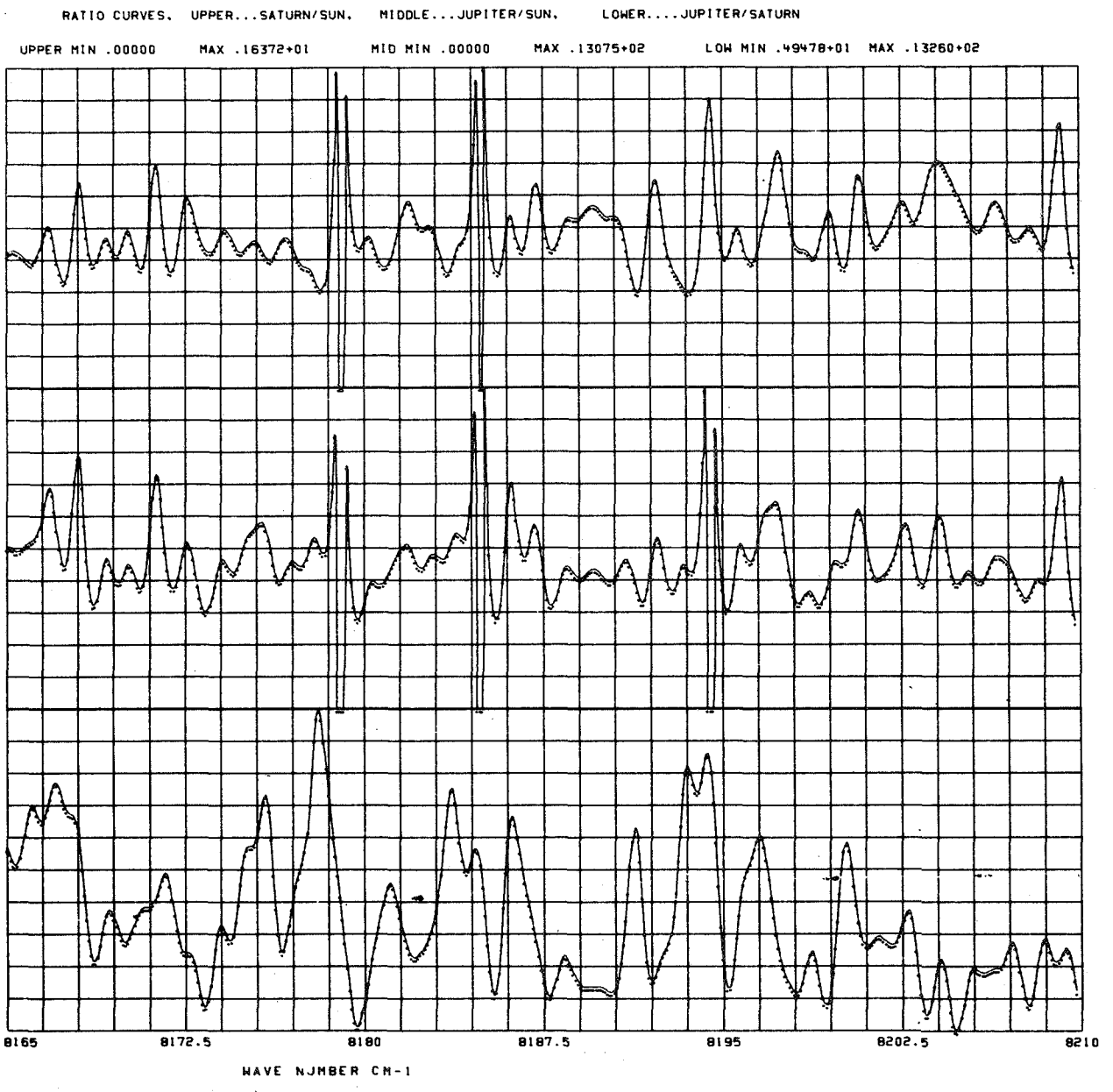


Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

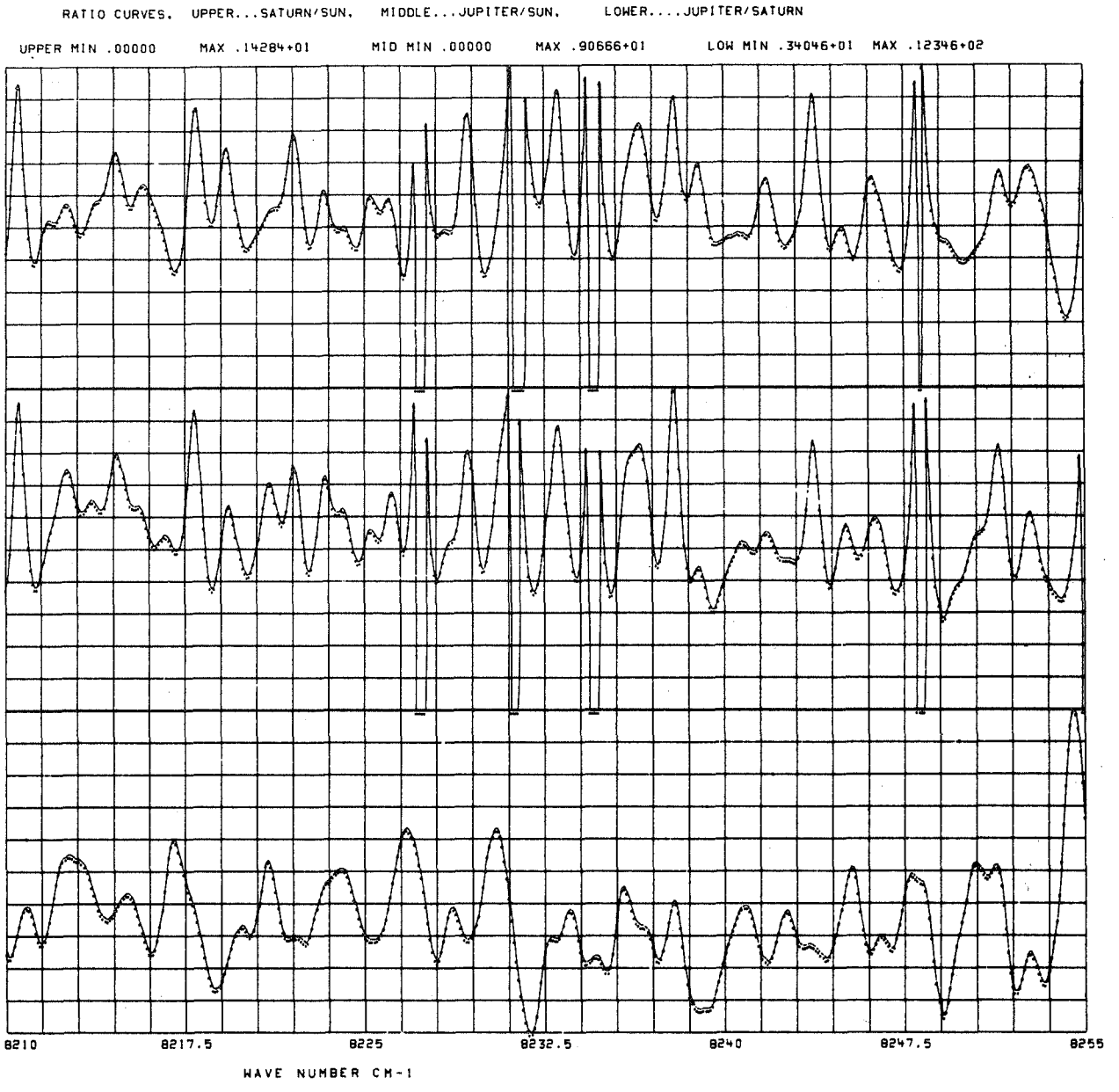
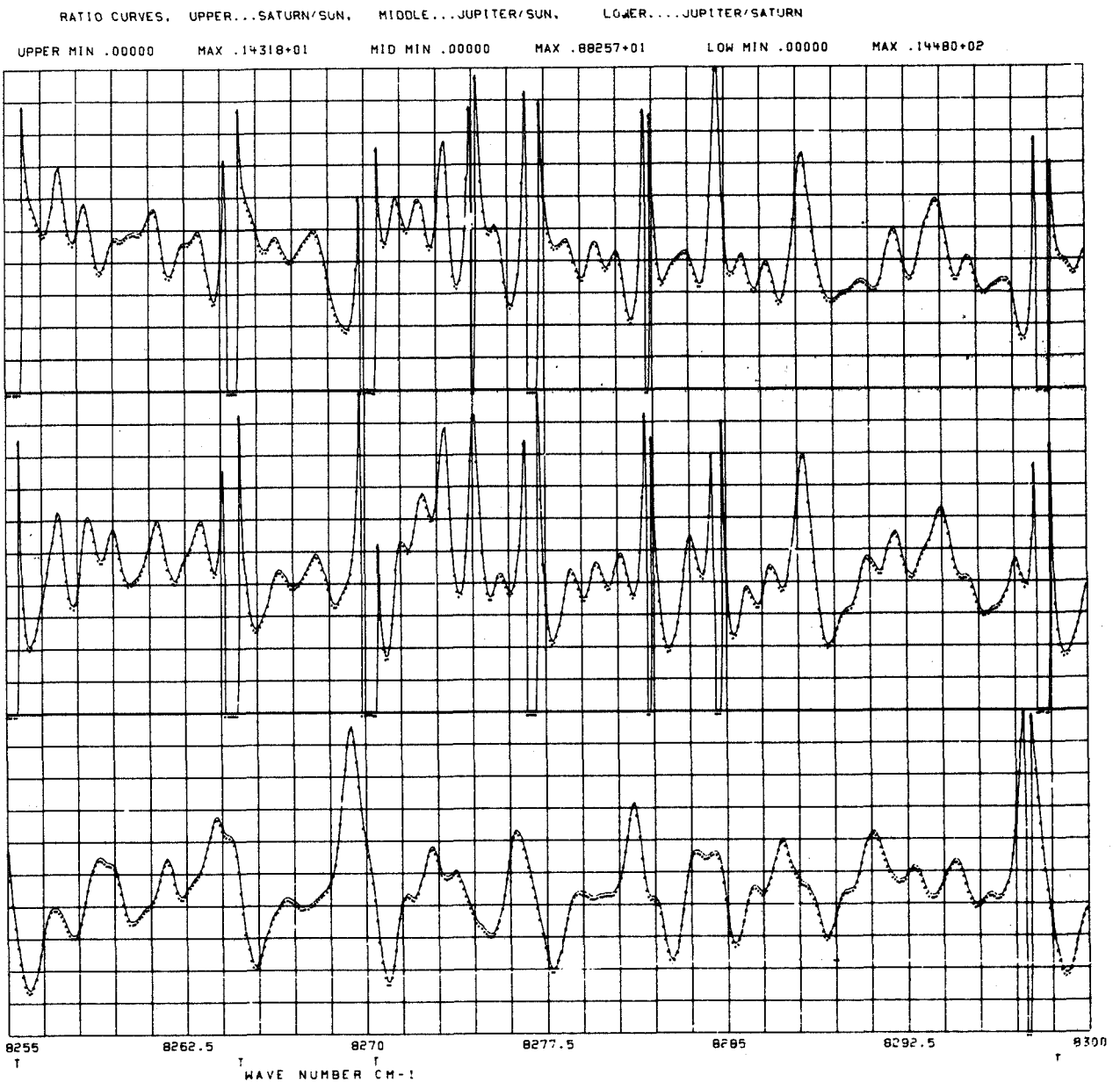


Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.



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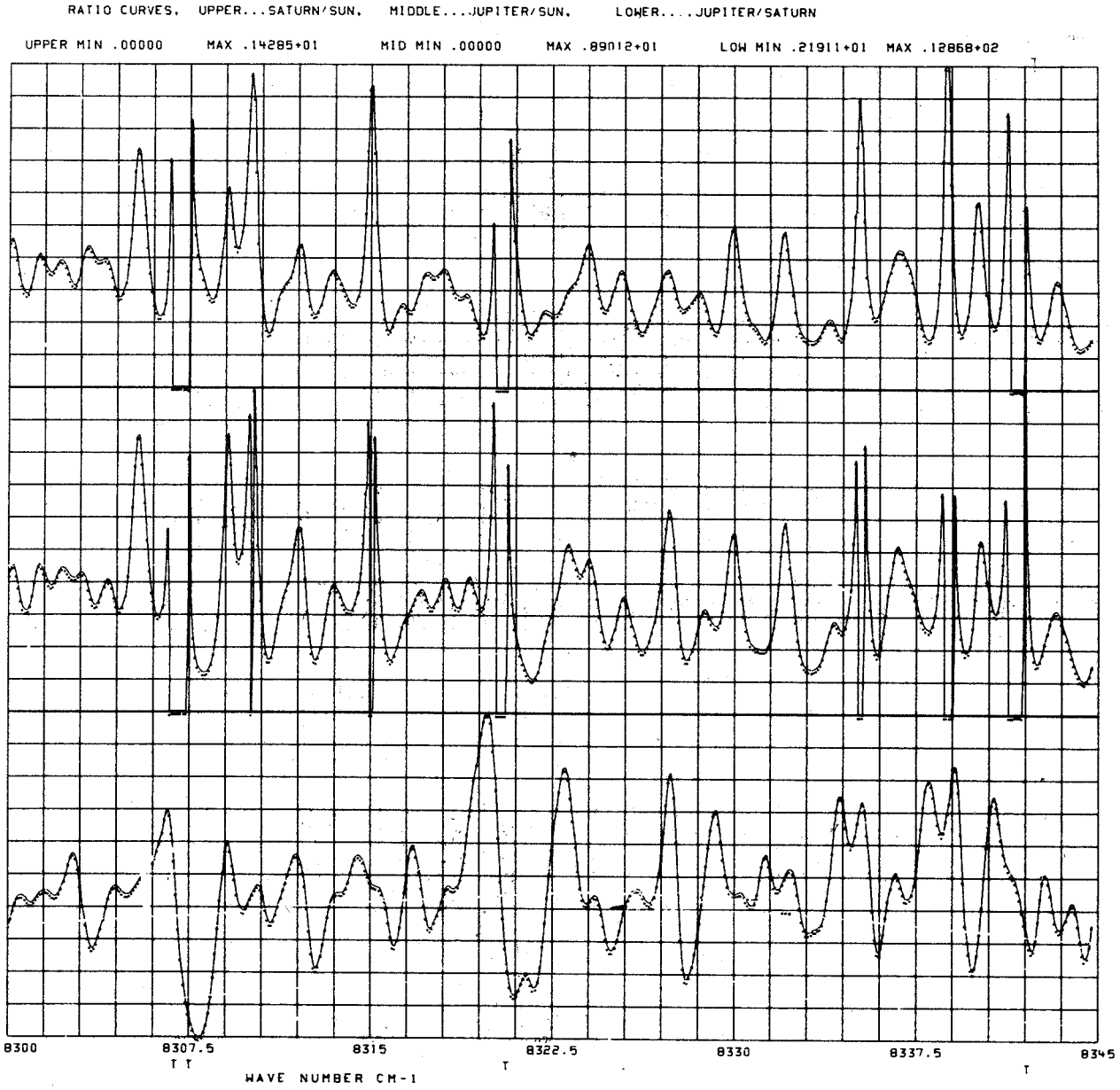

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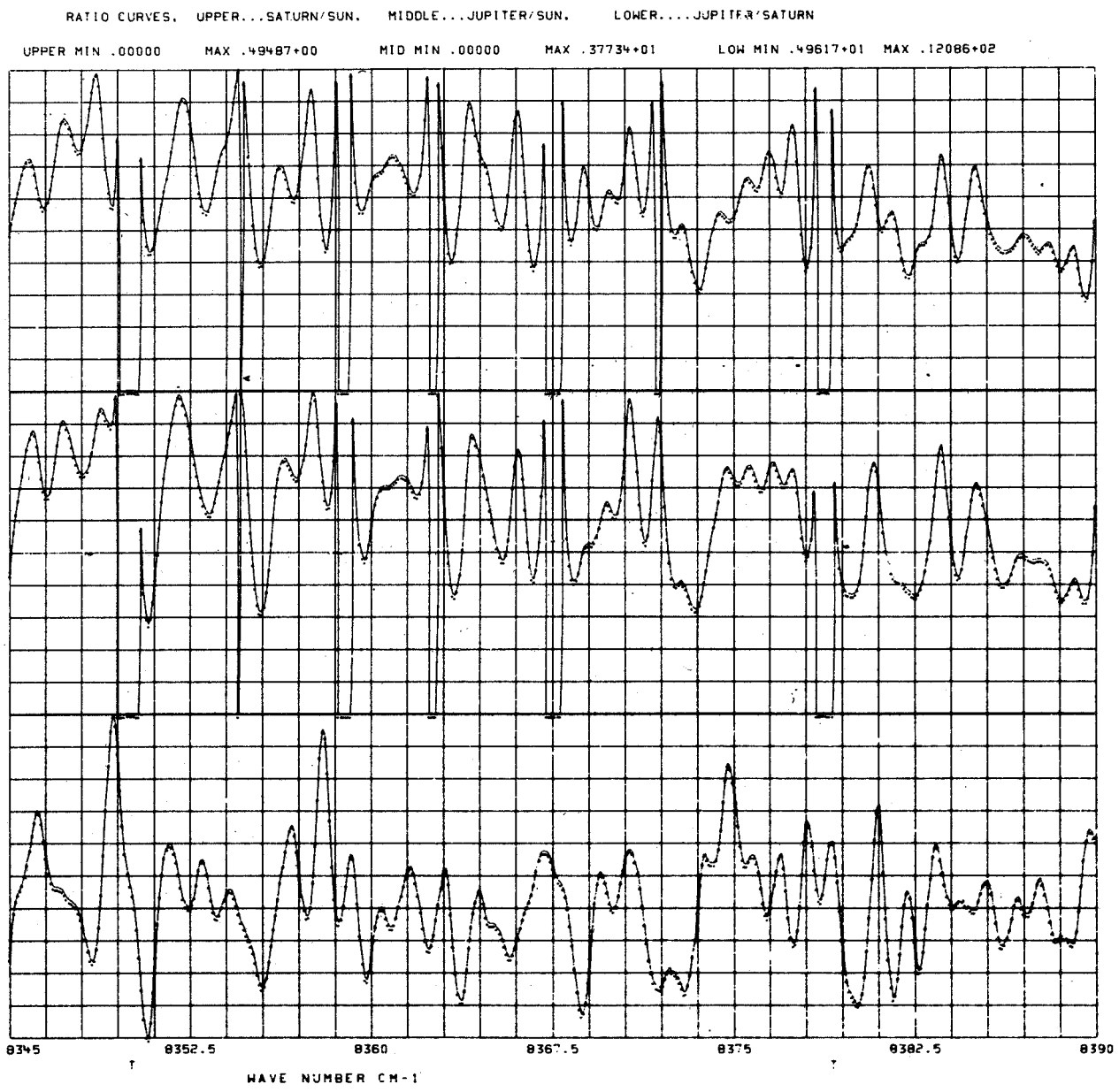

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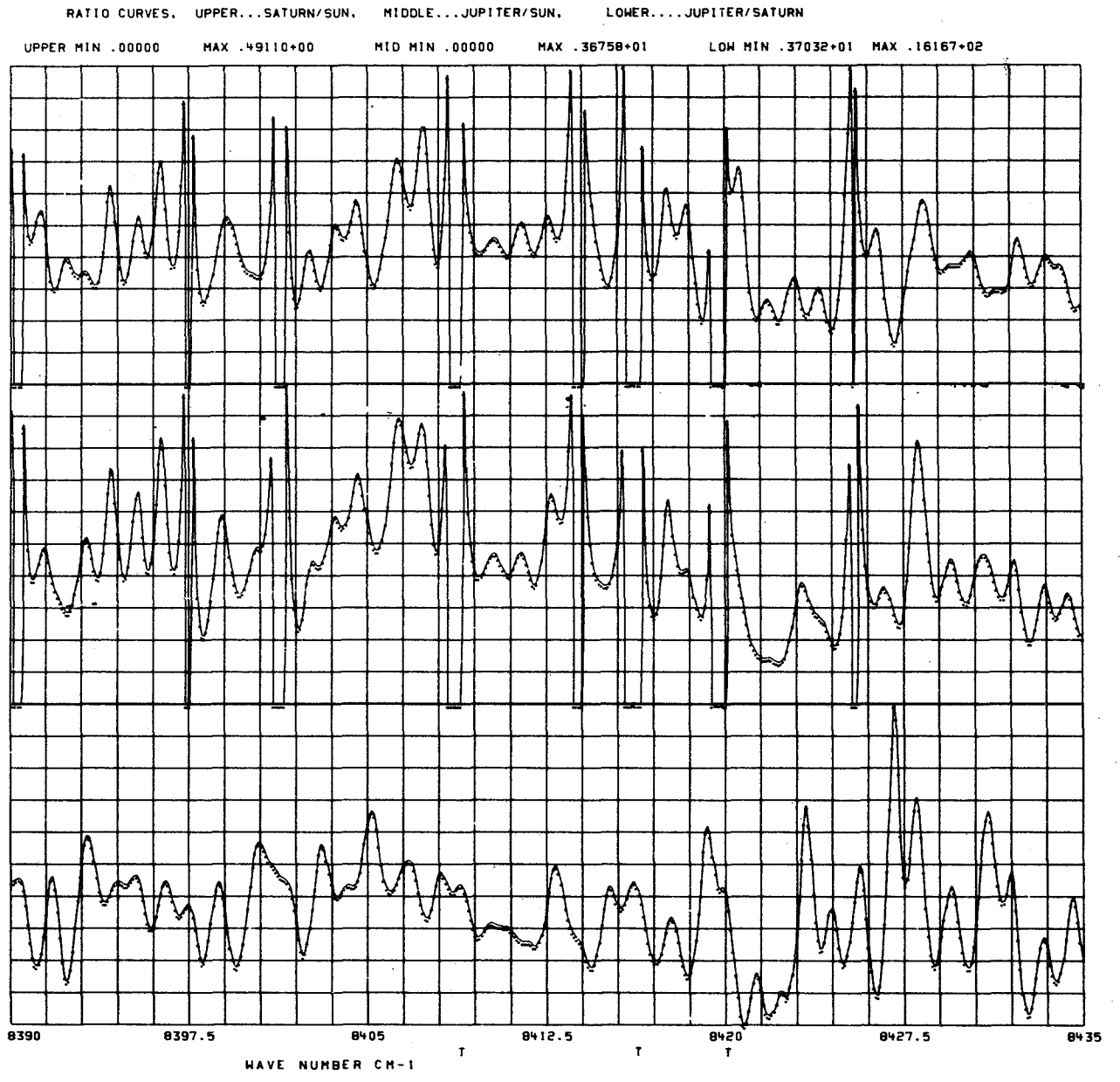

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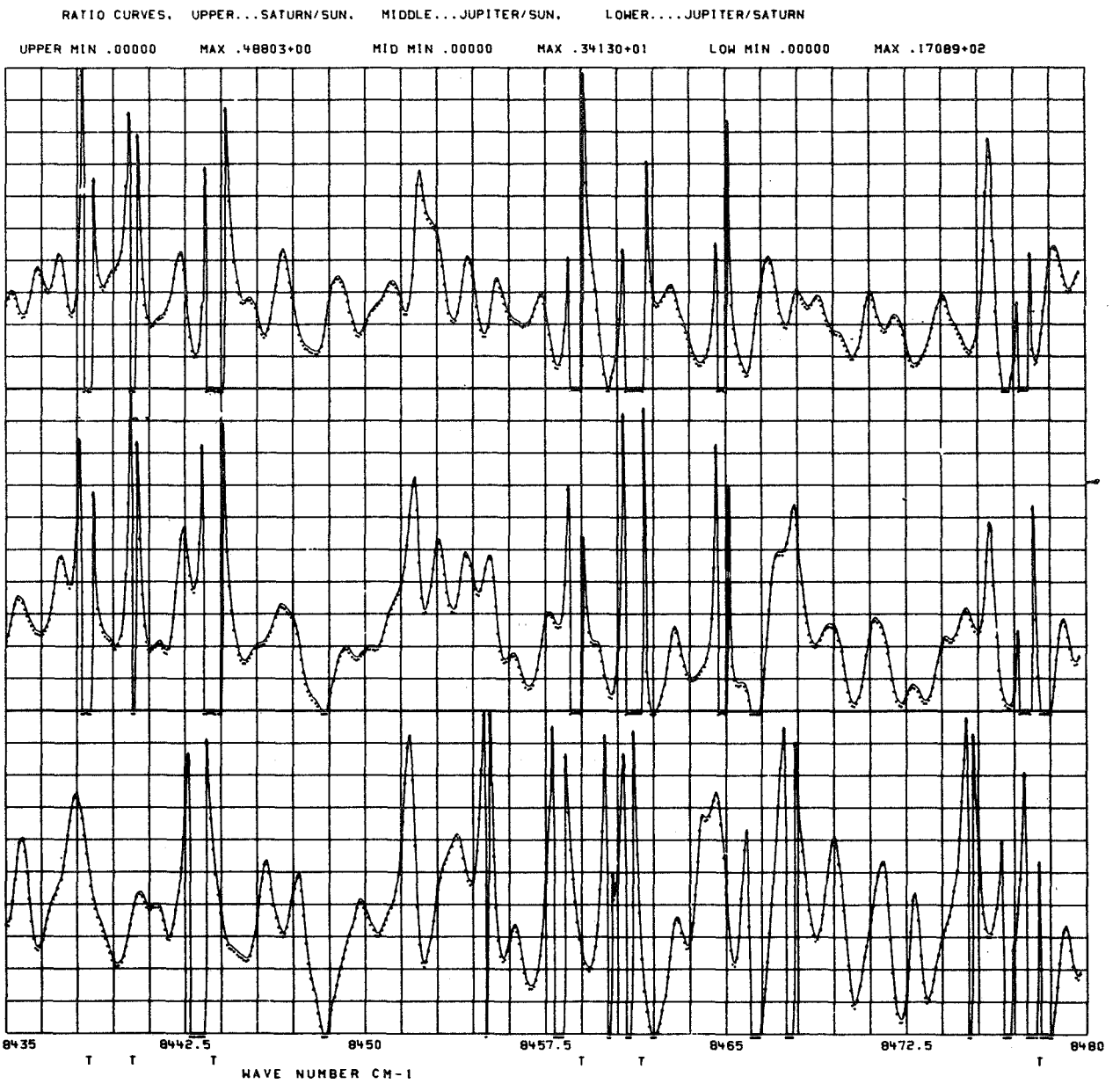
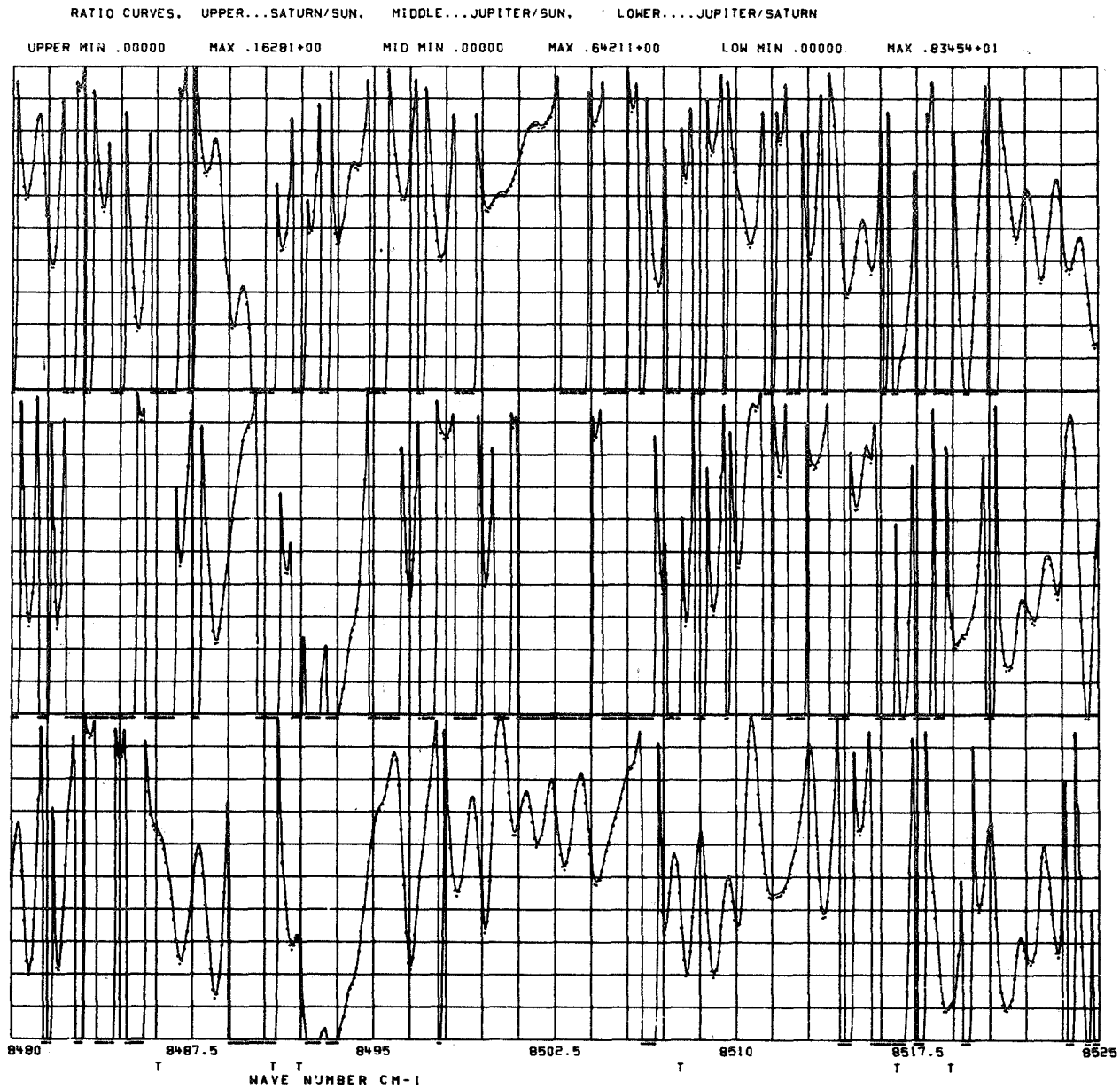


Figure 4 (*continued*).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.



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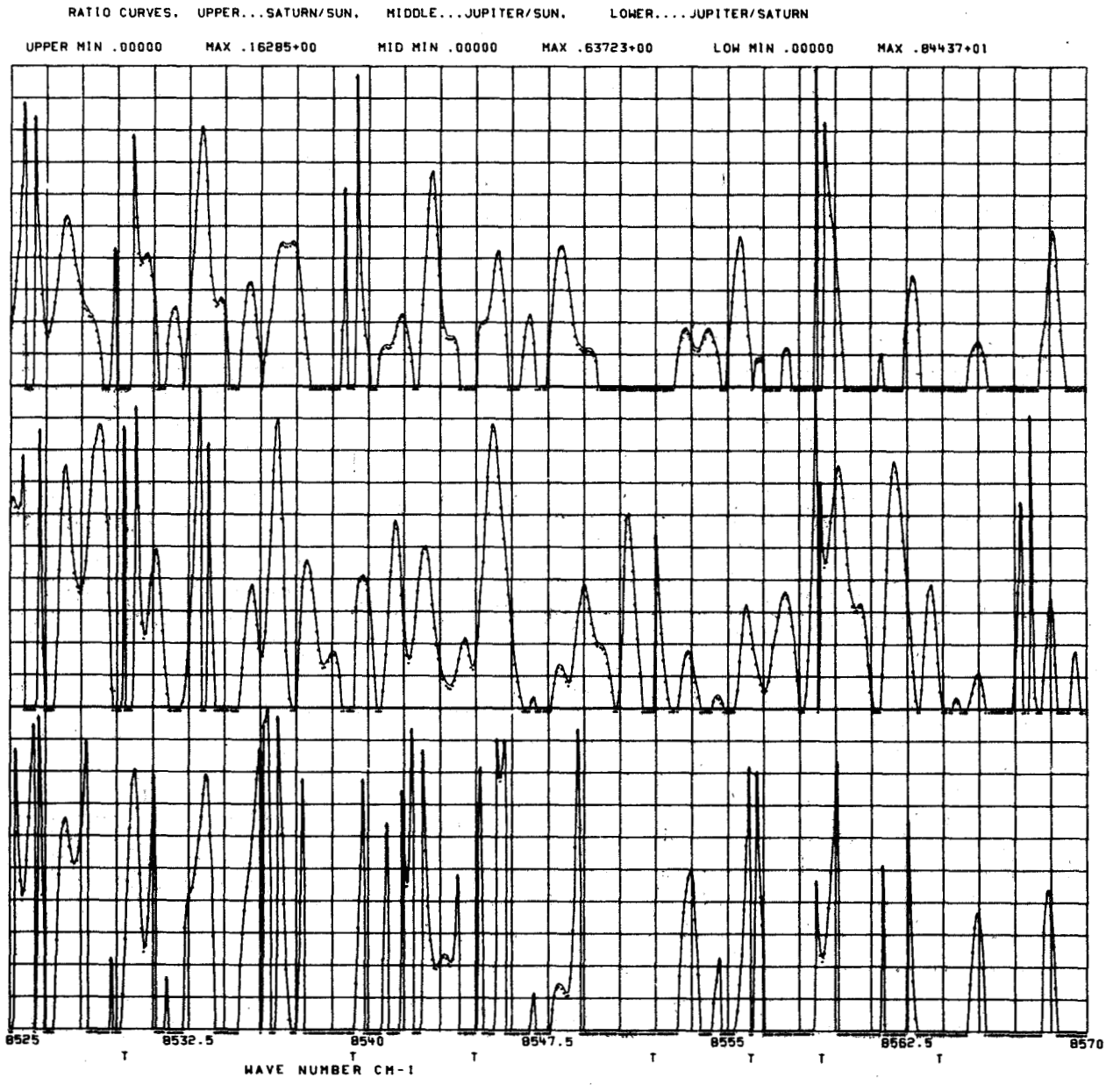

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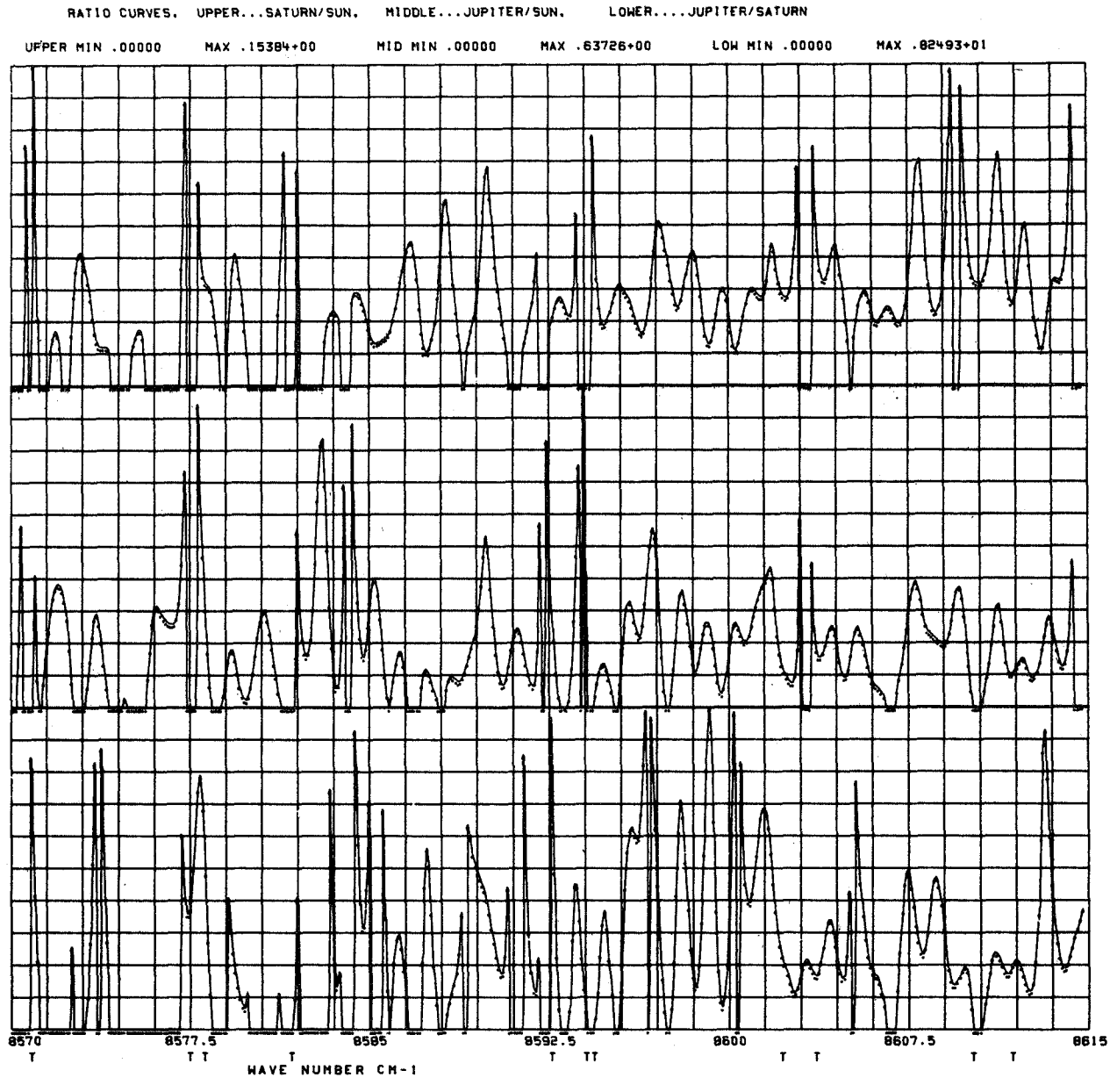

Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

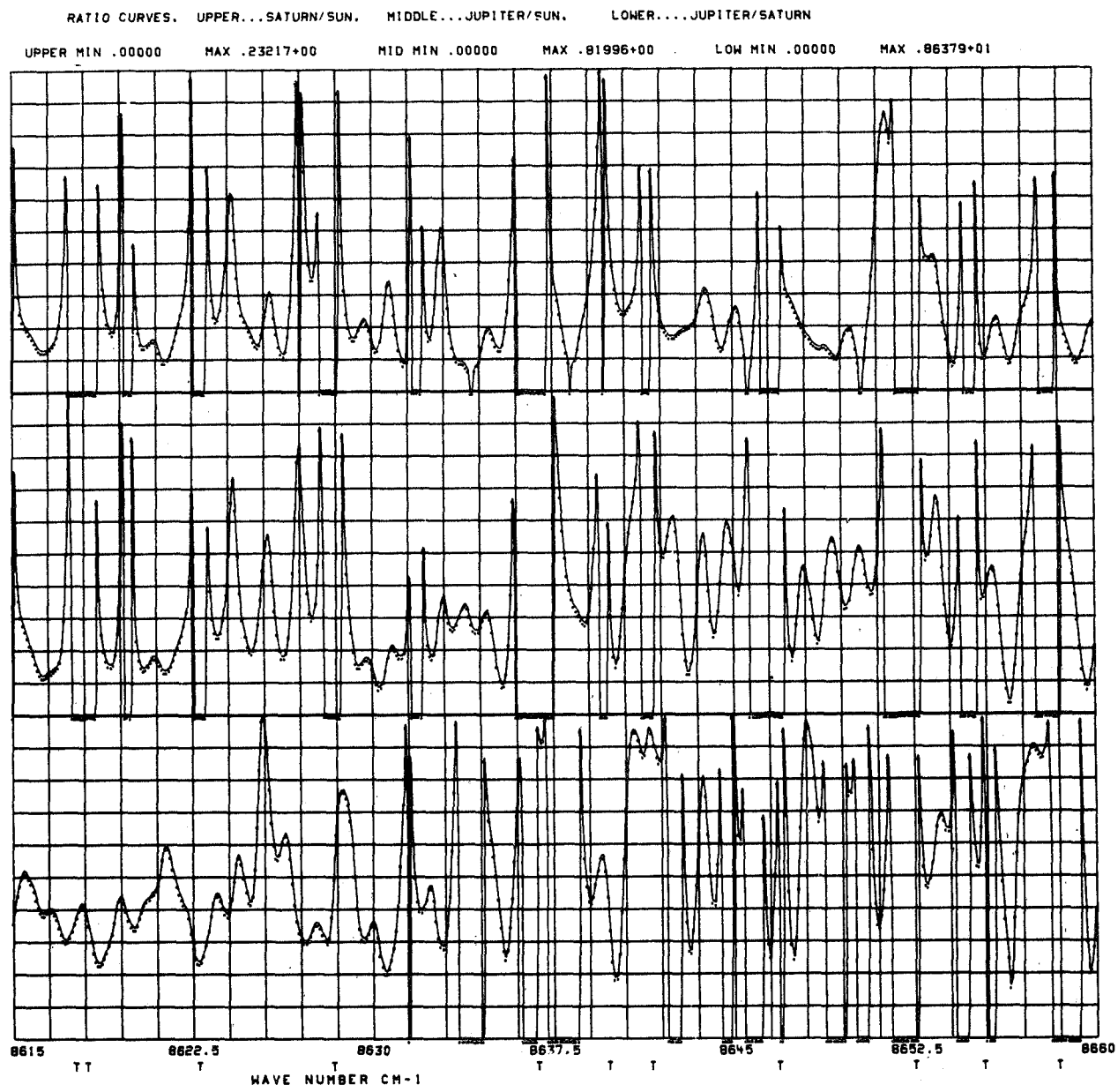

Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

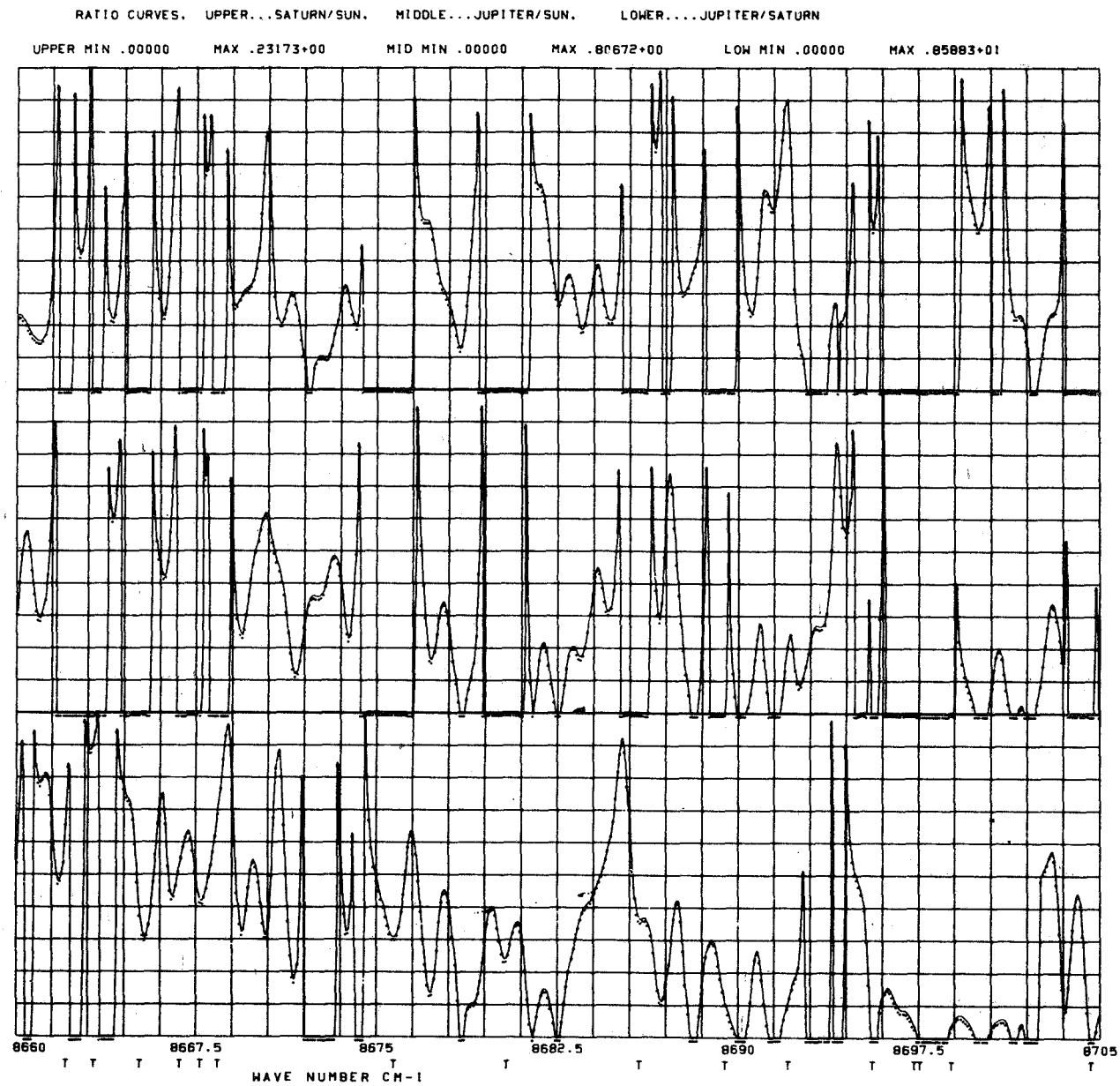

Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

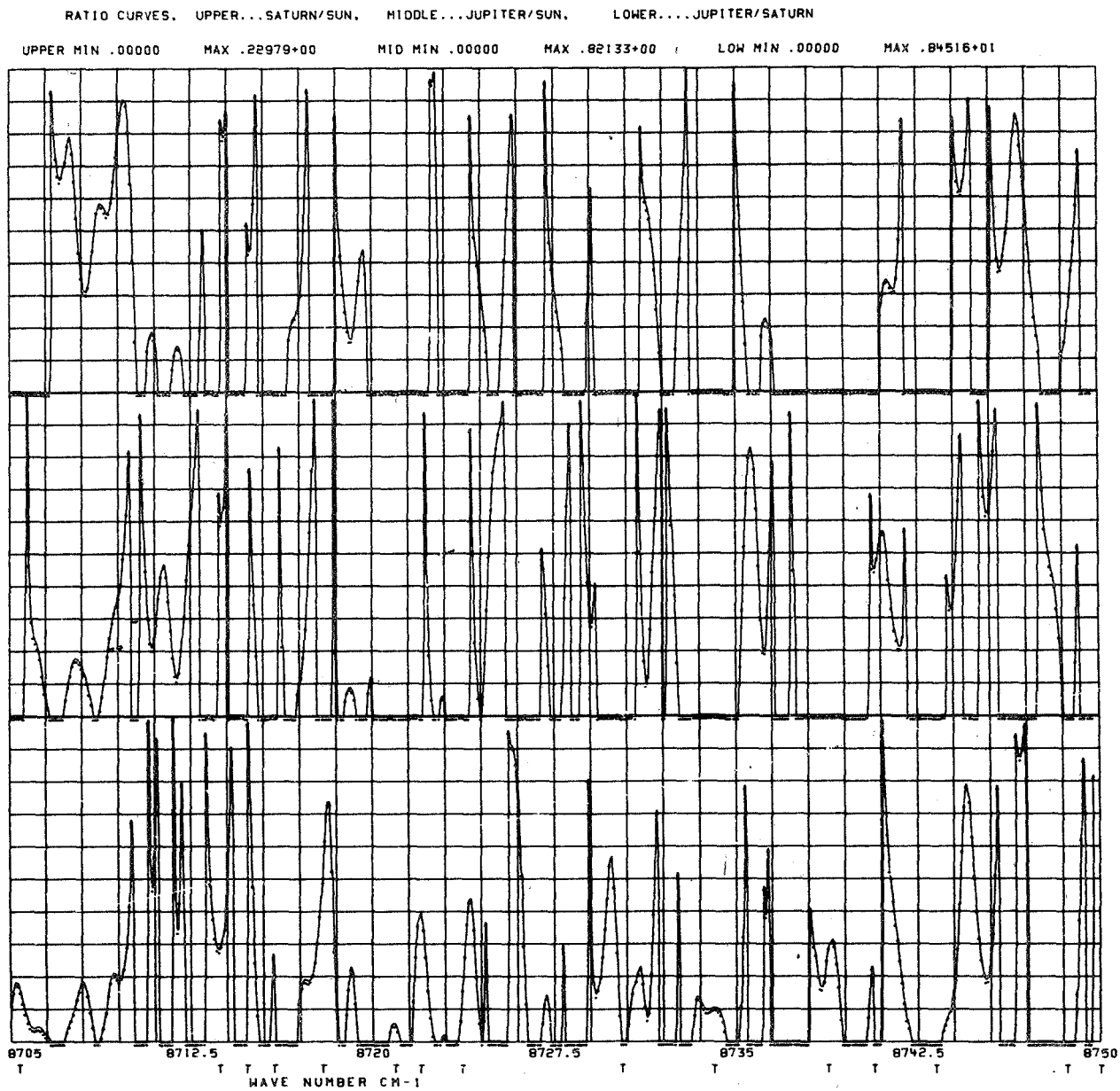

Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

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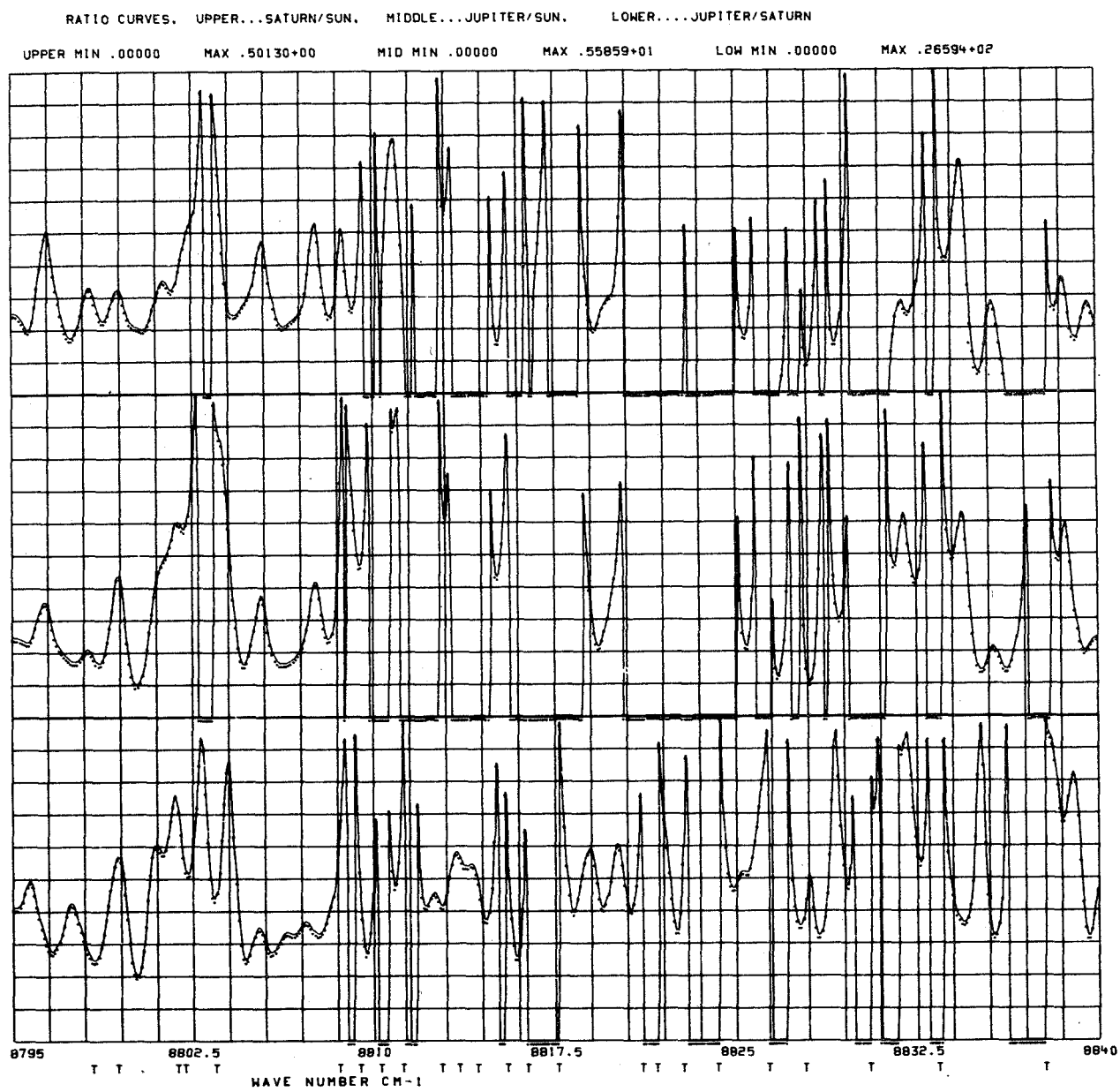

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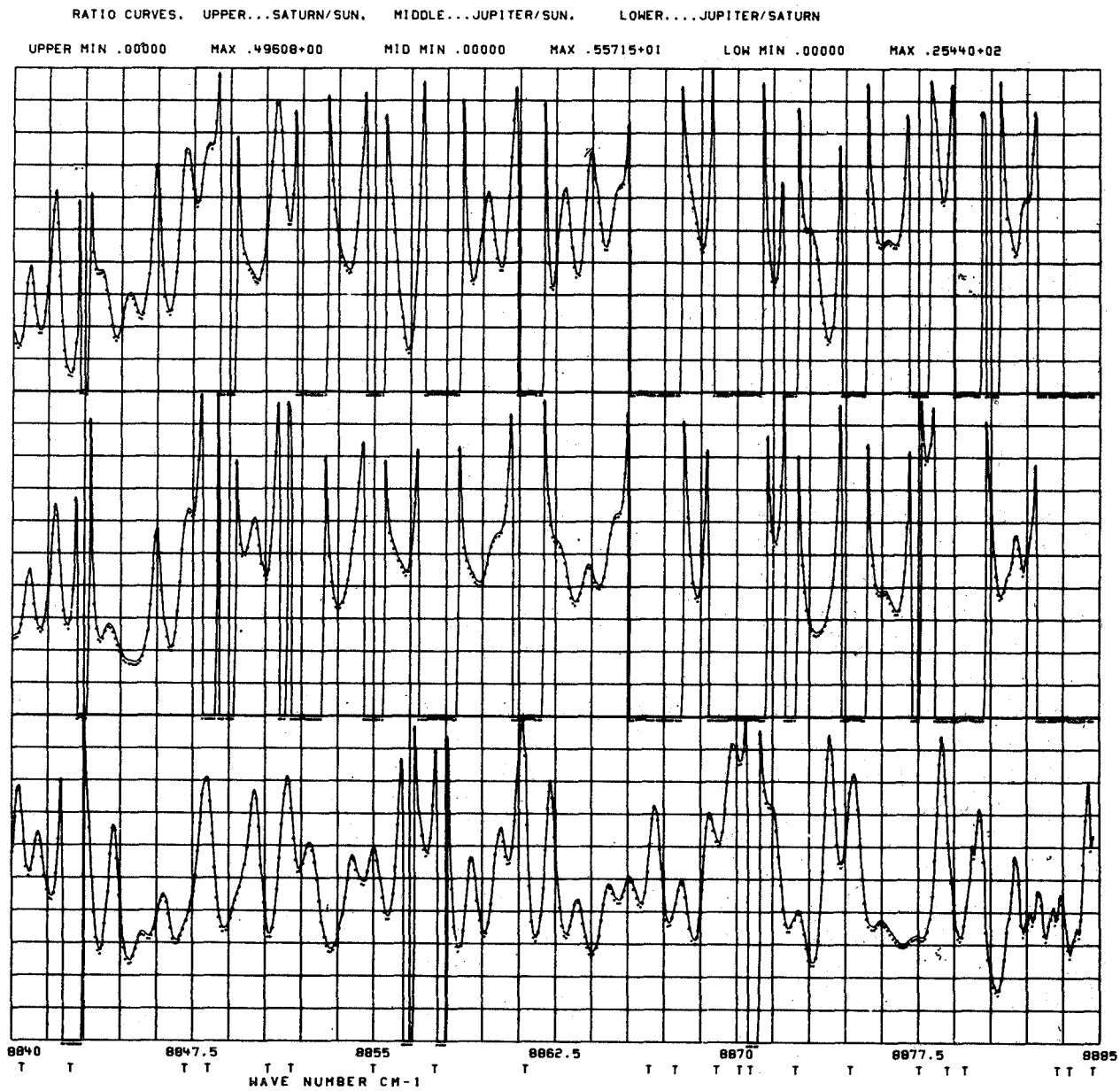

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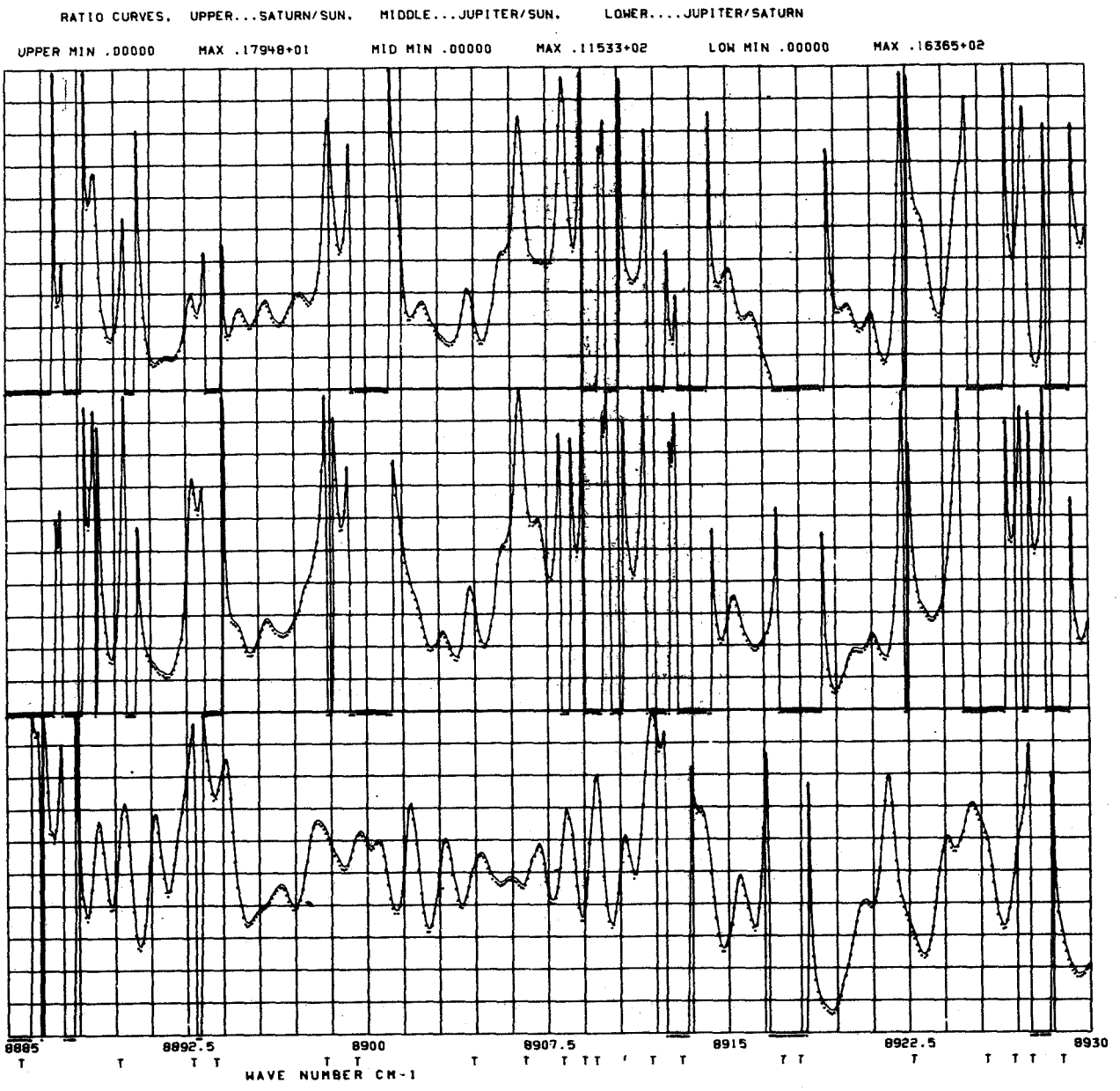

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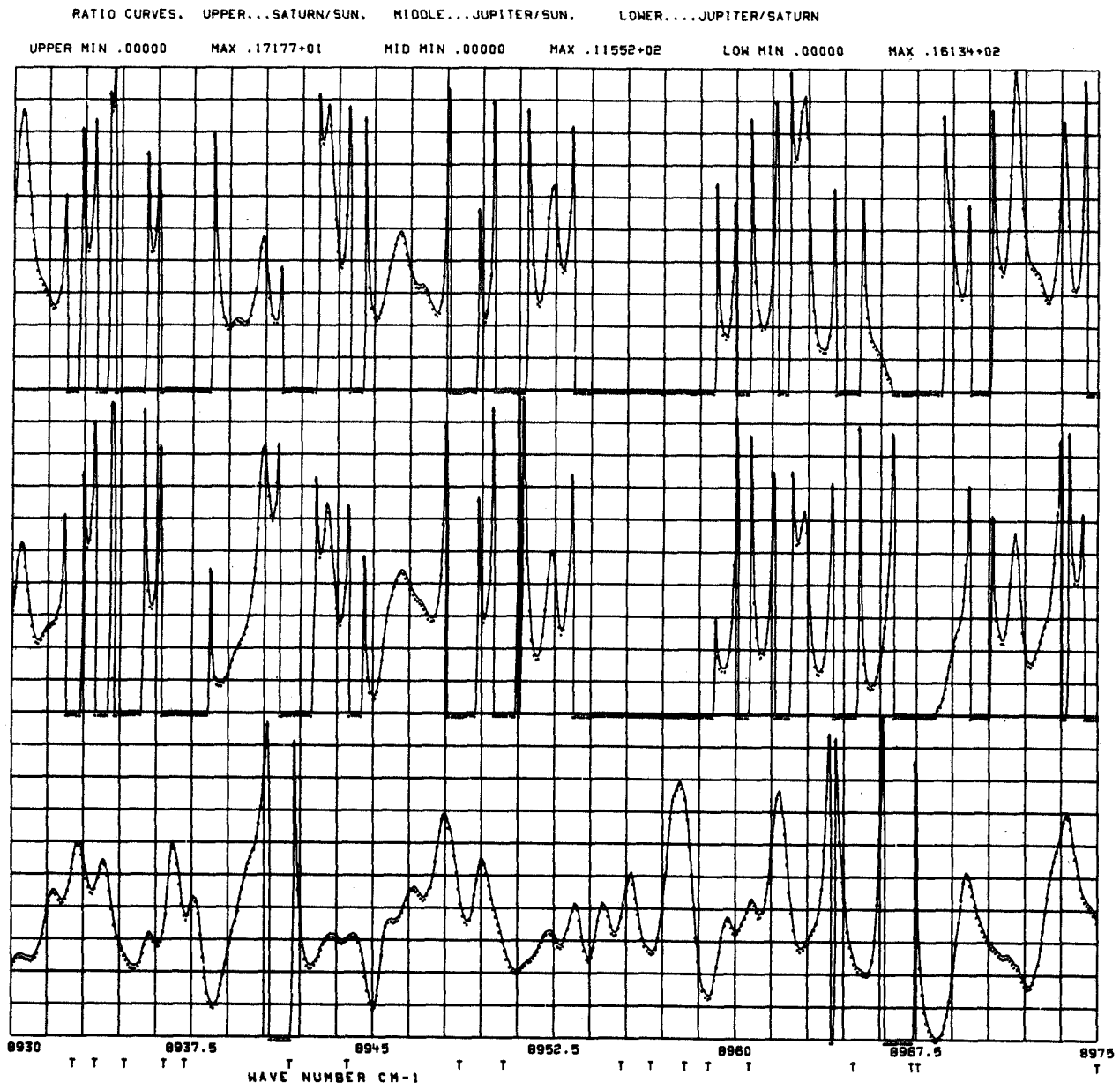

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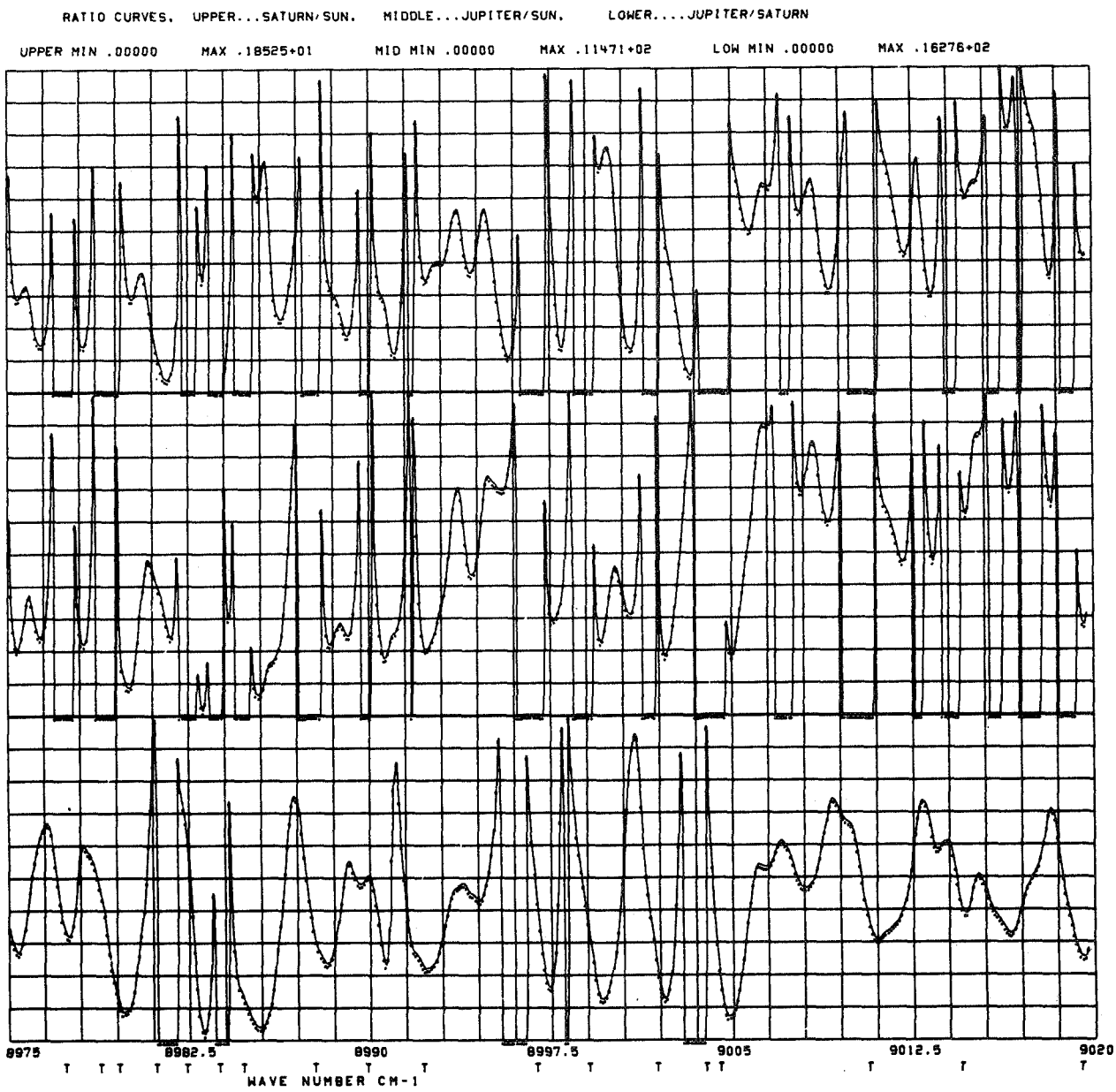

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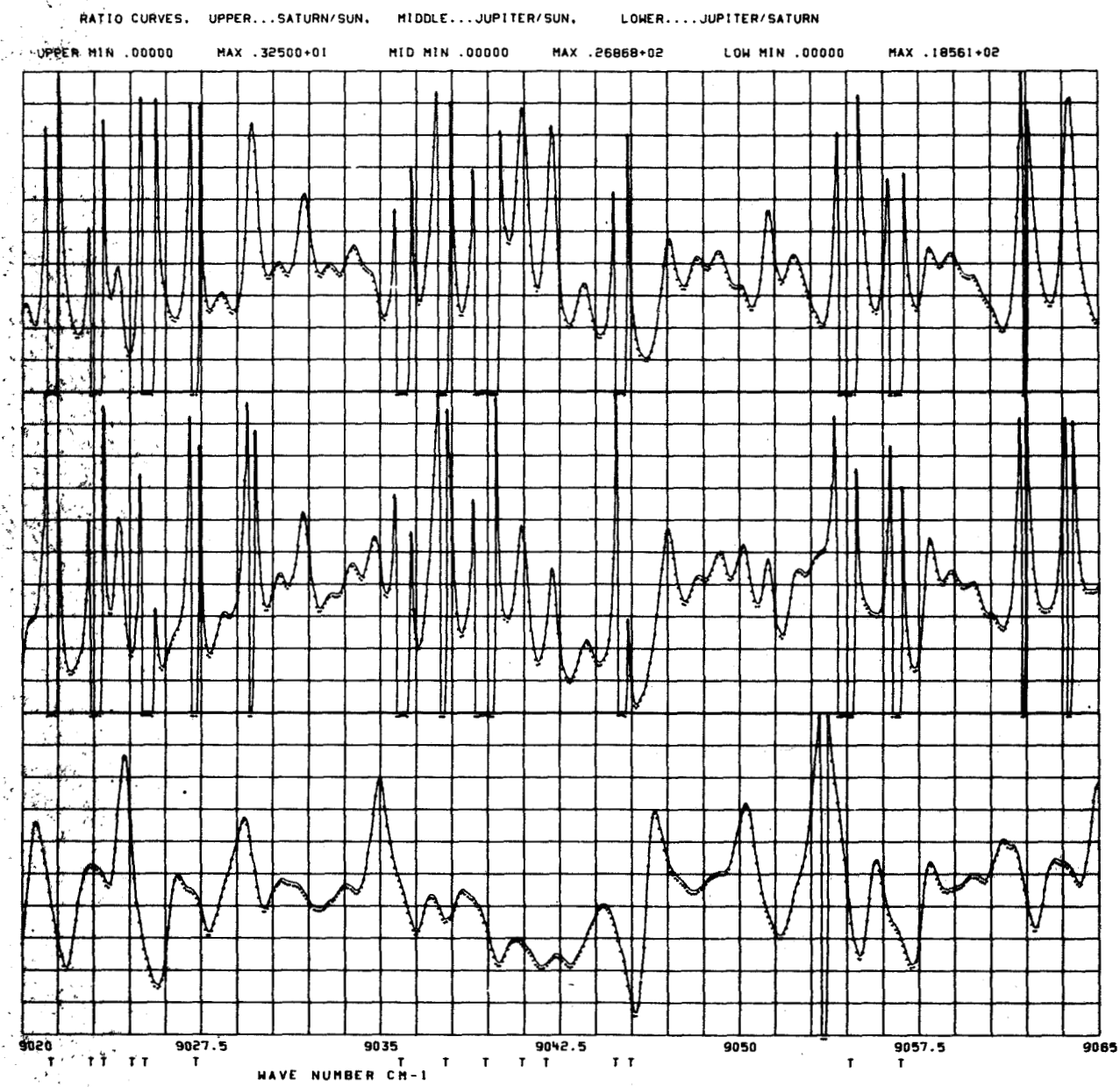

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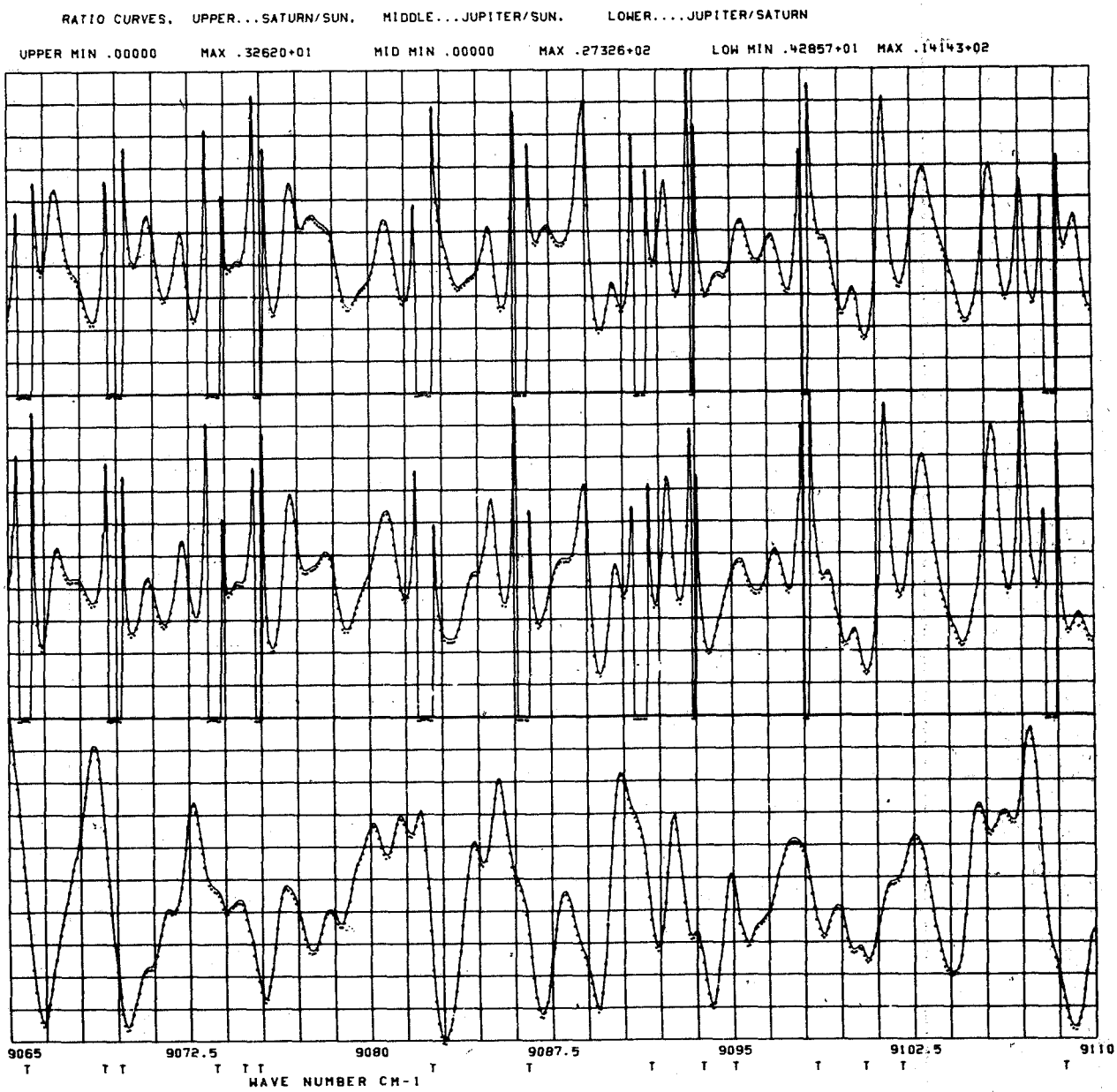

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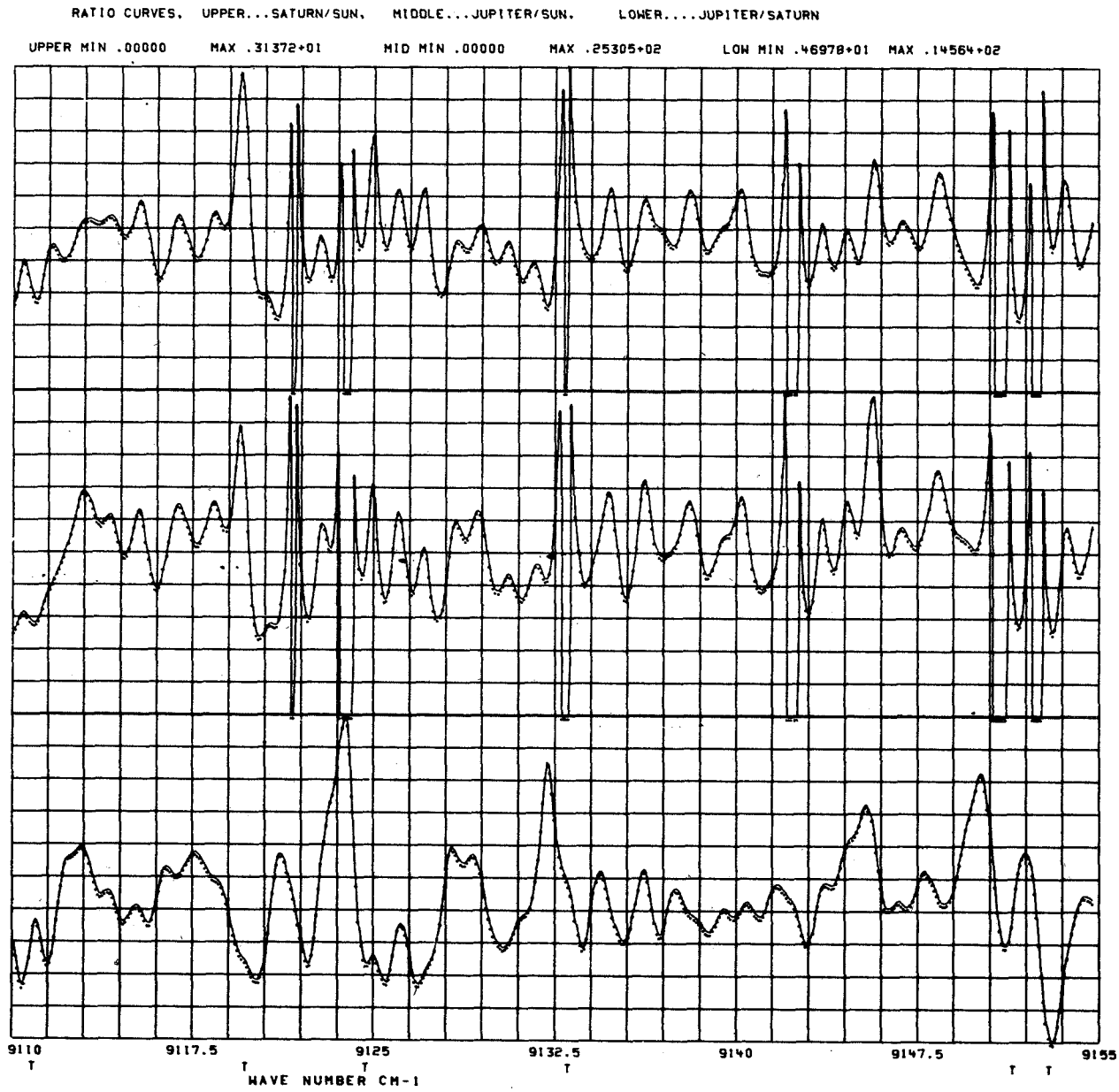

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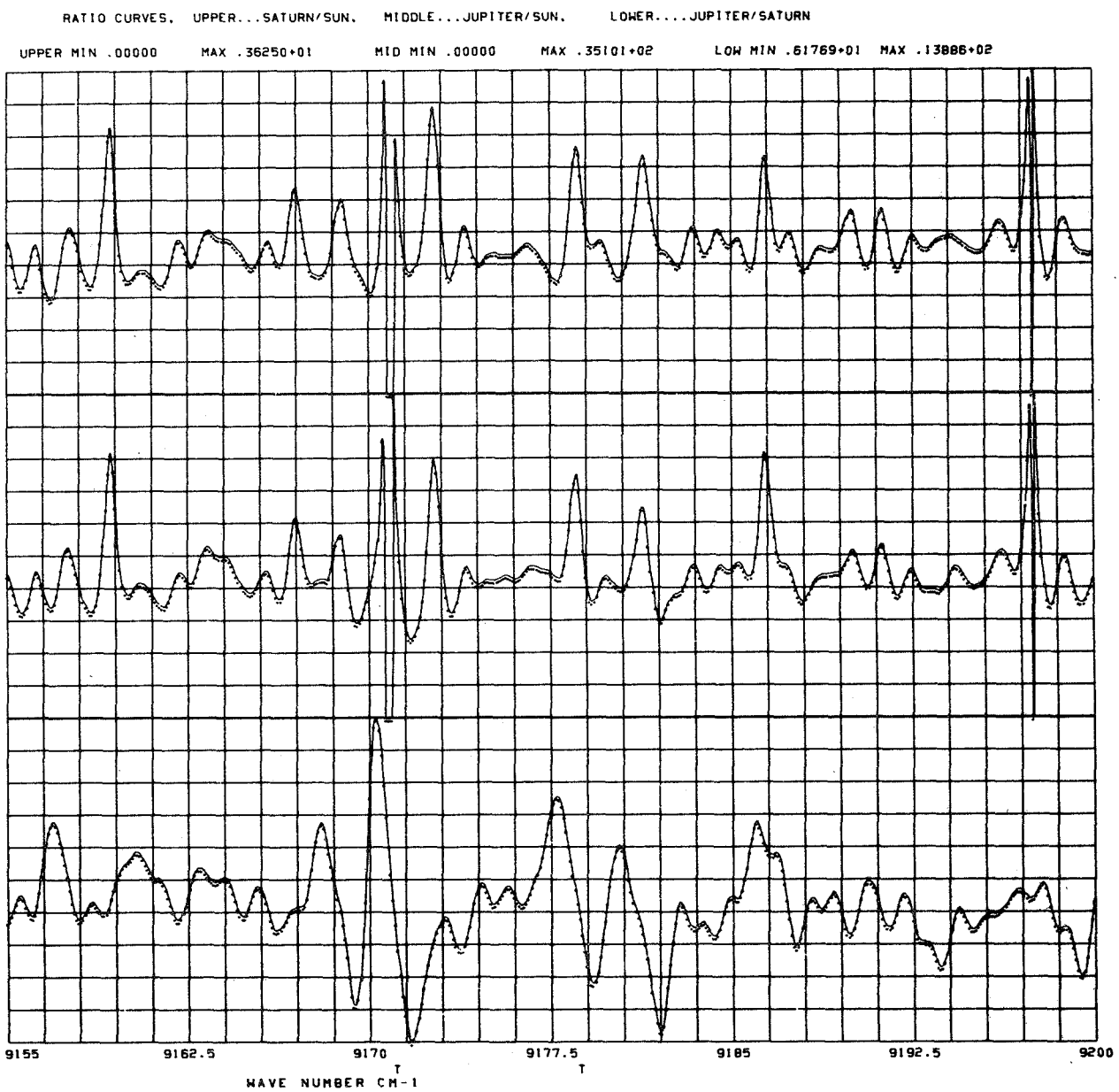

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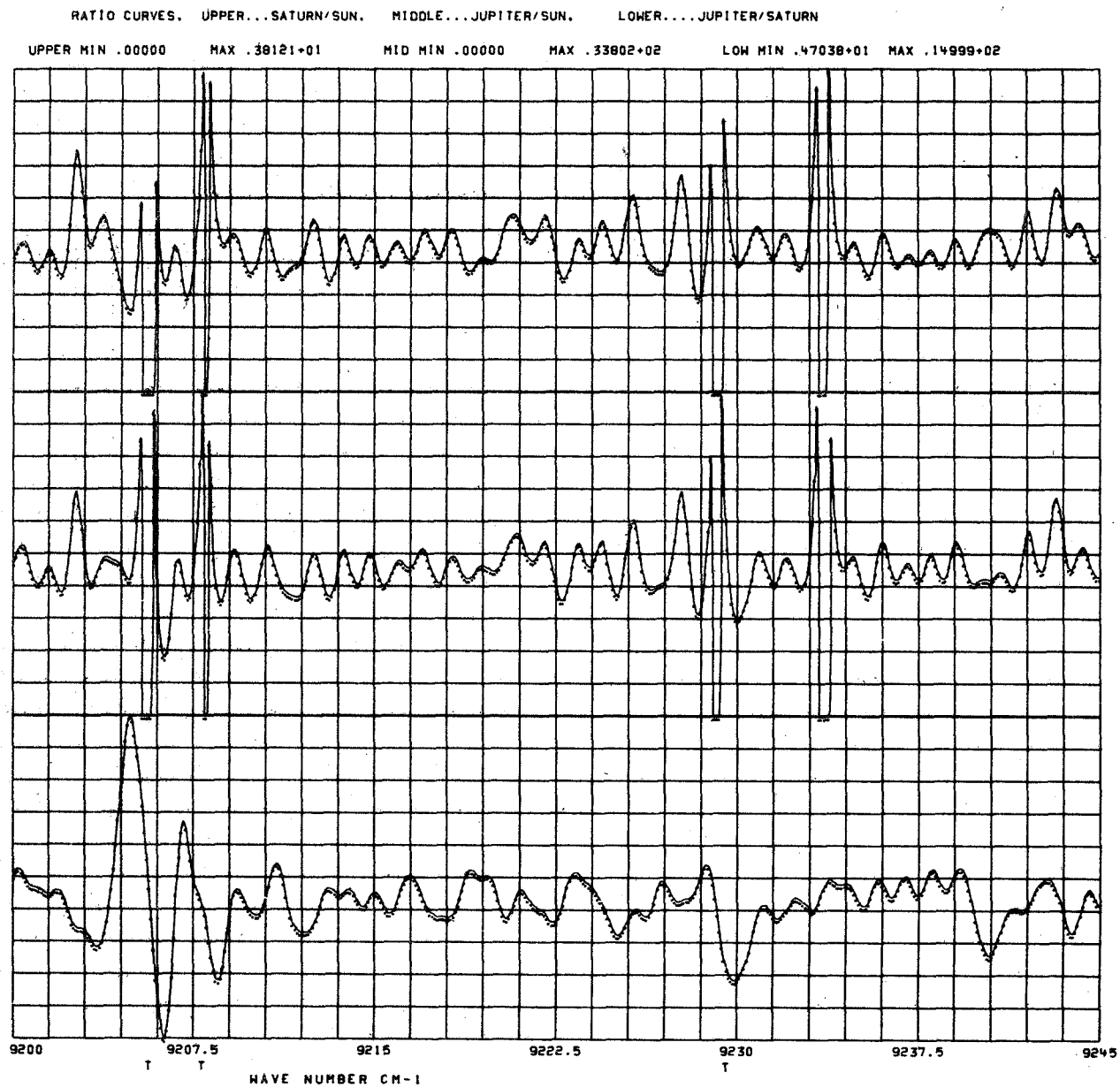

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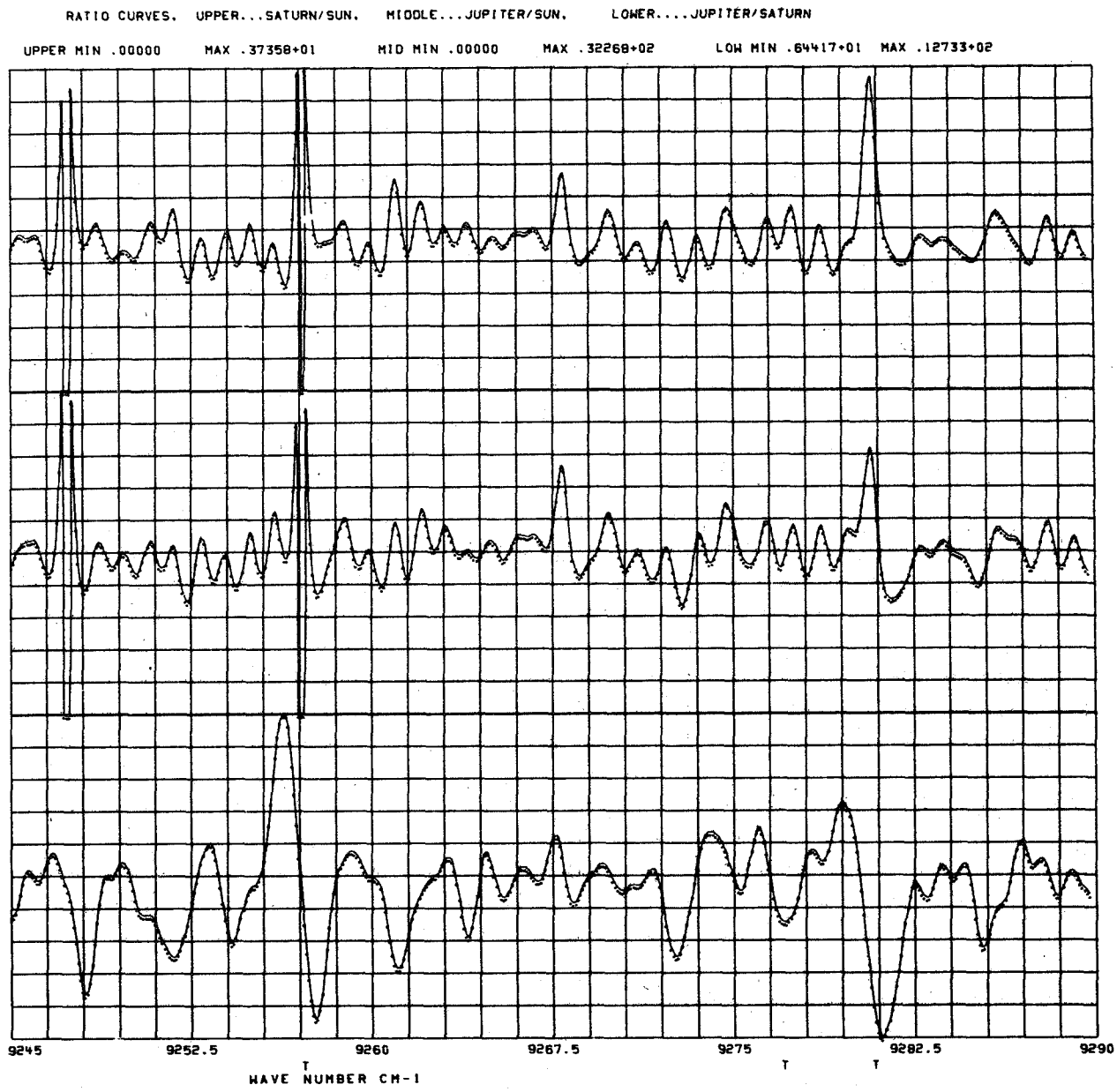

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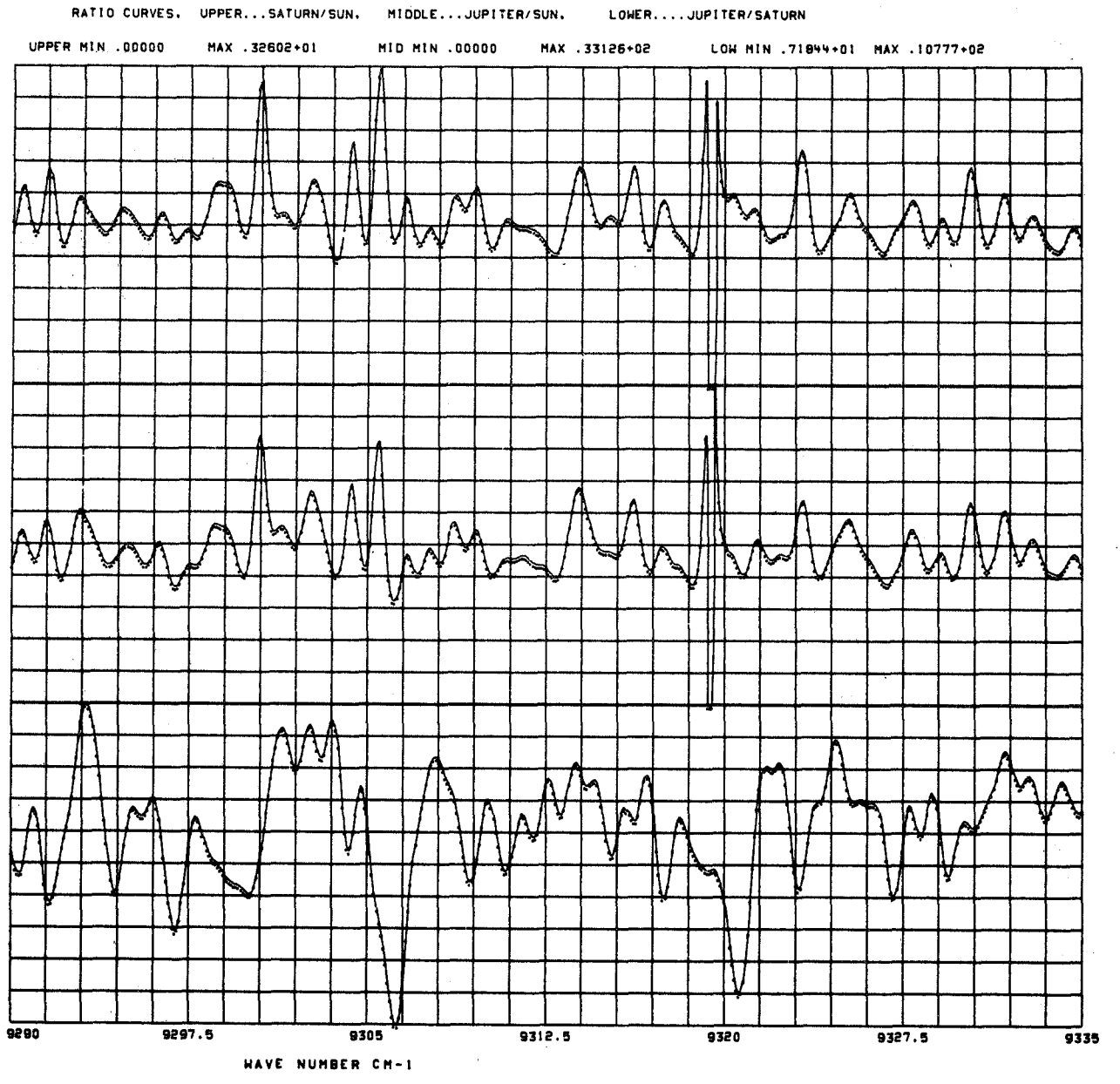

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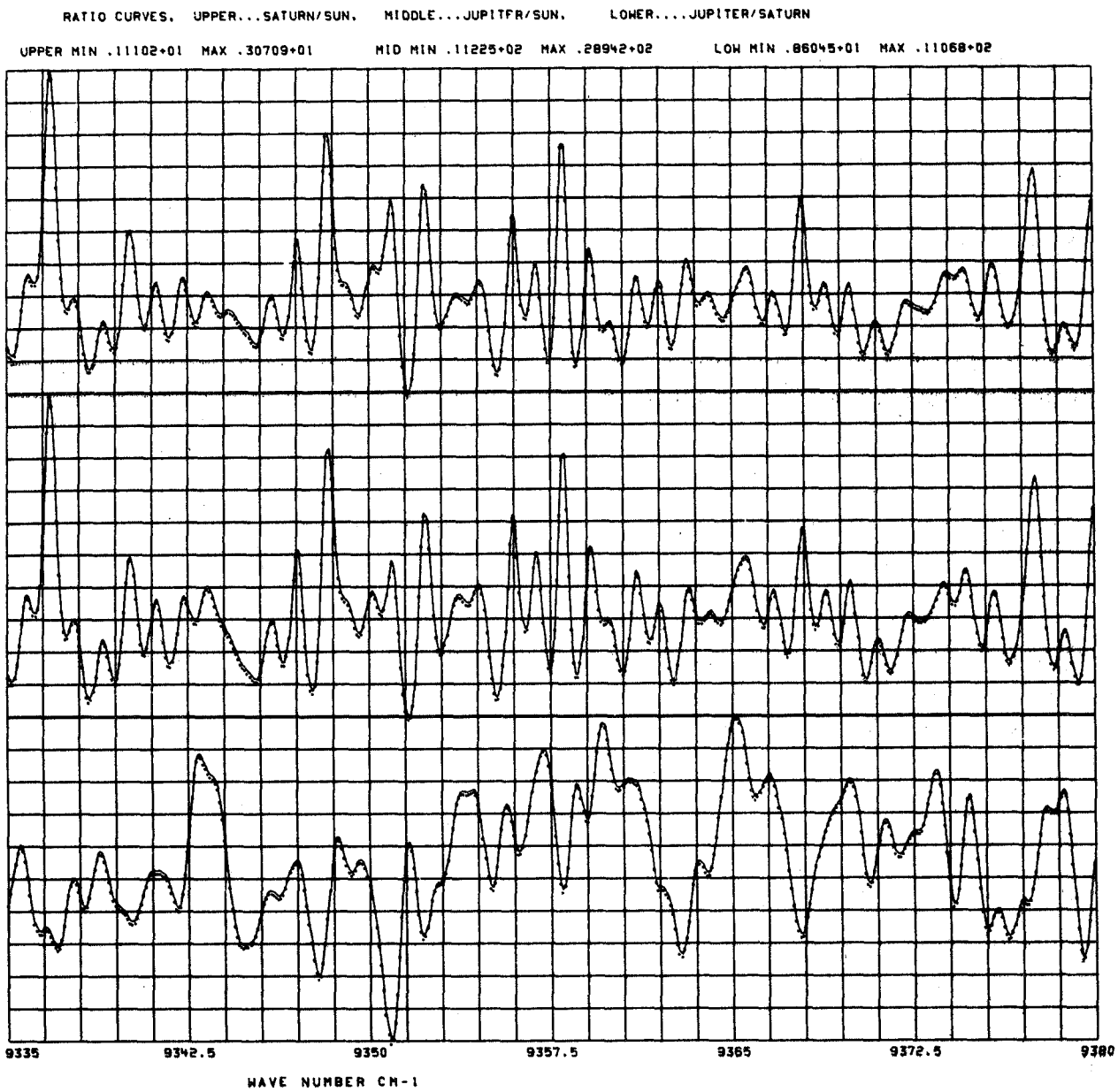

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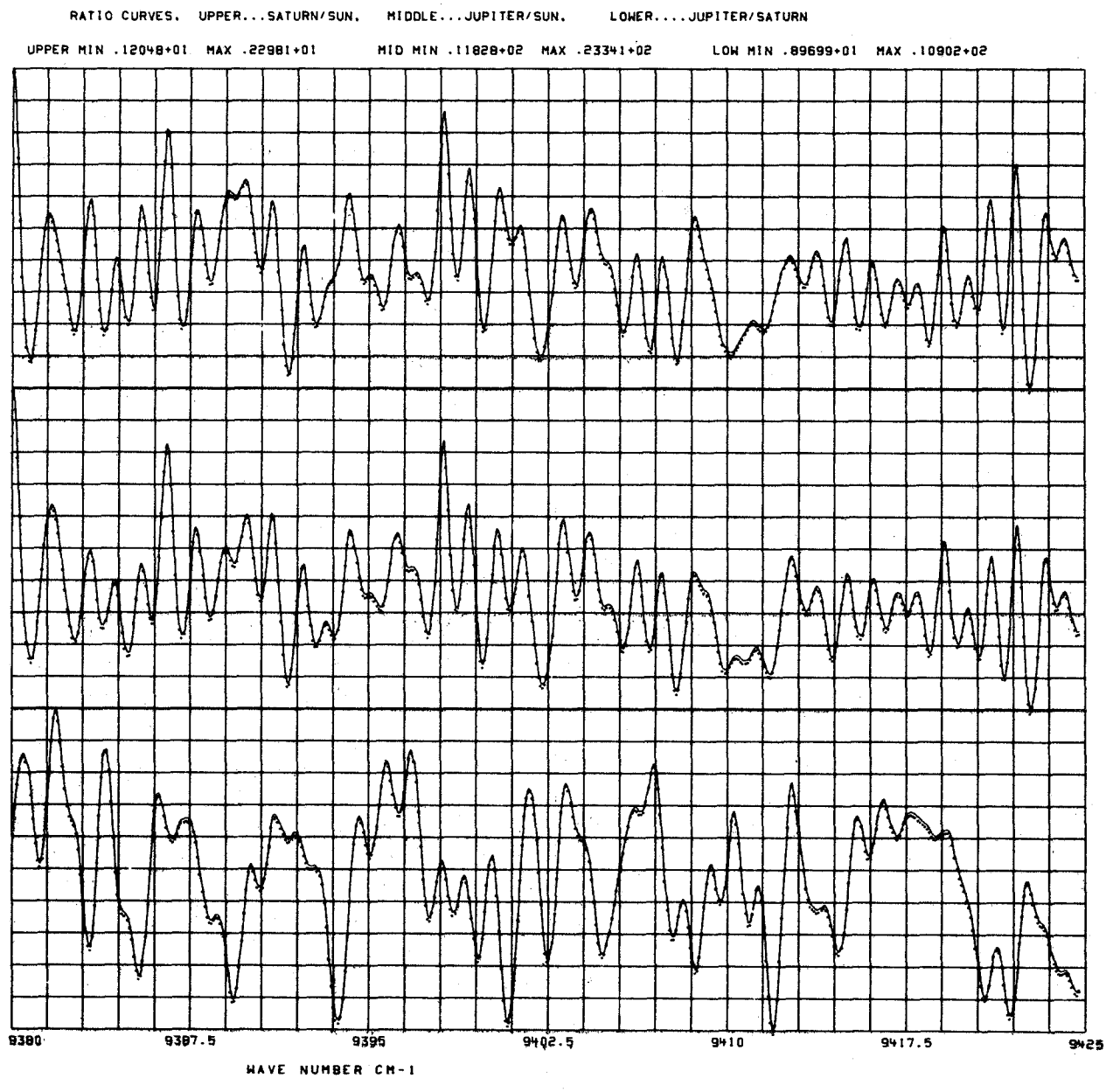

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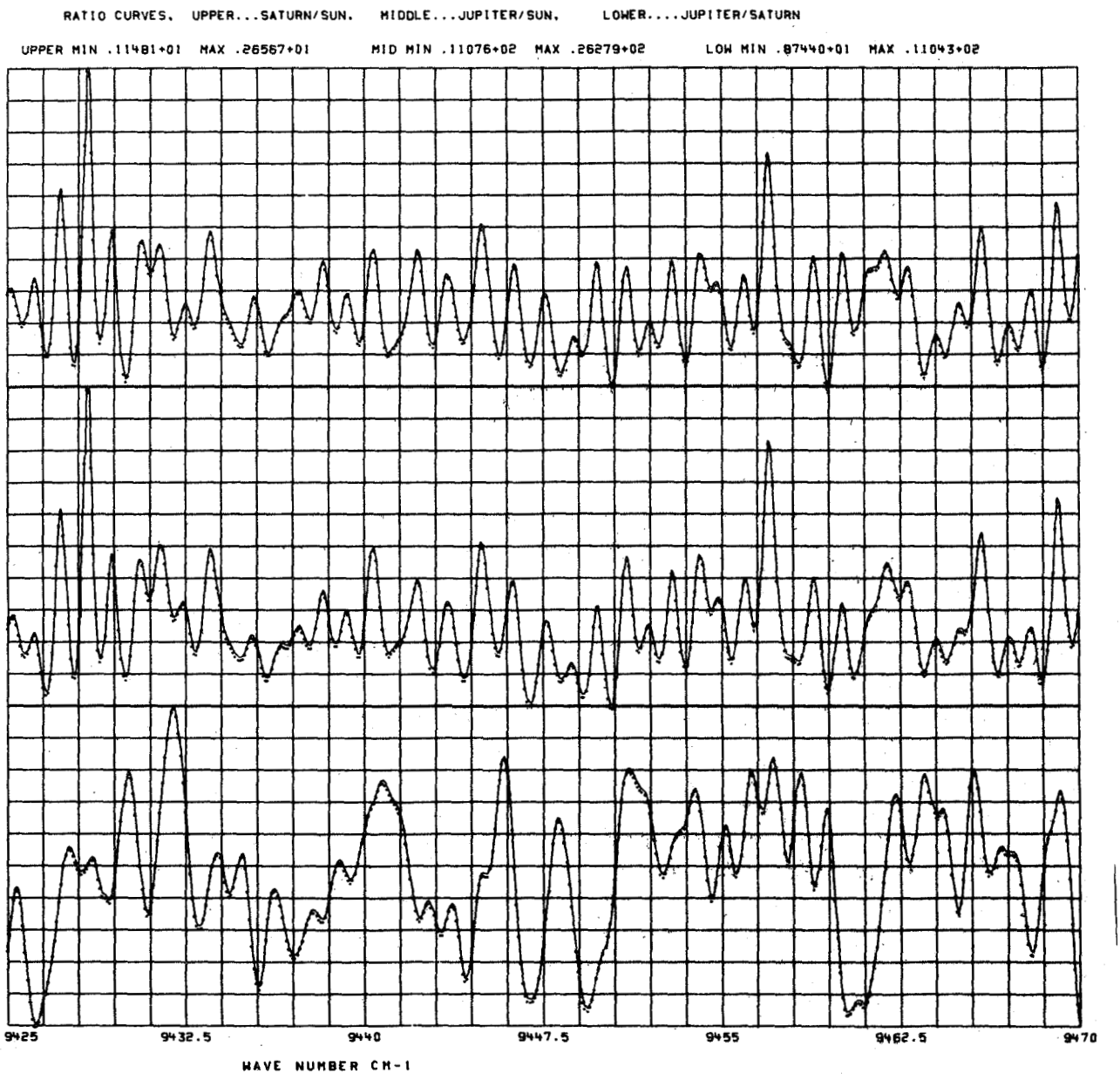

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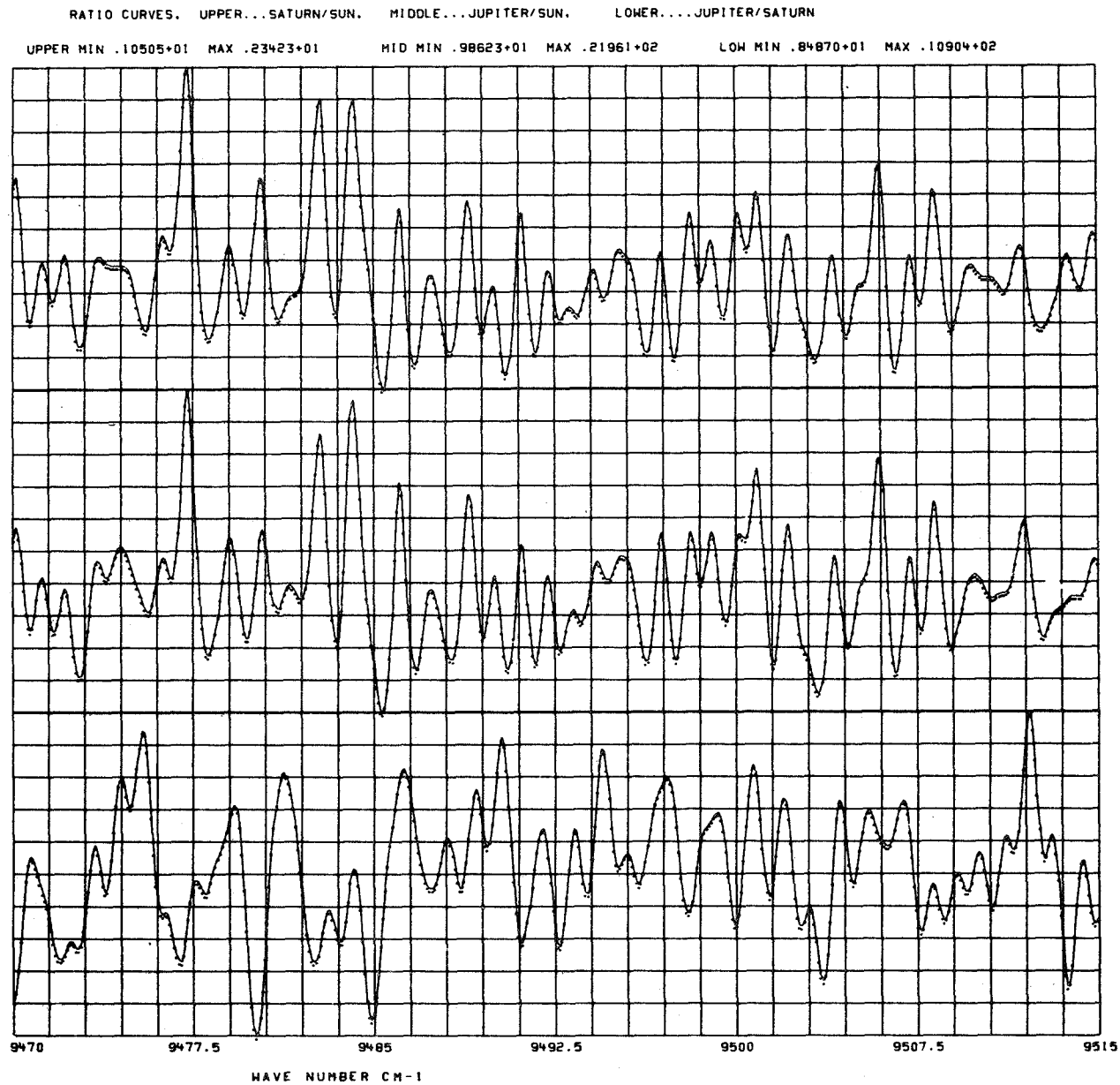

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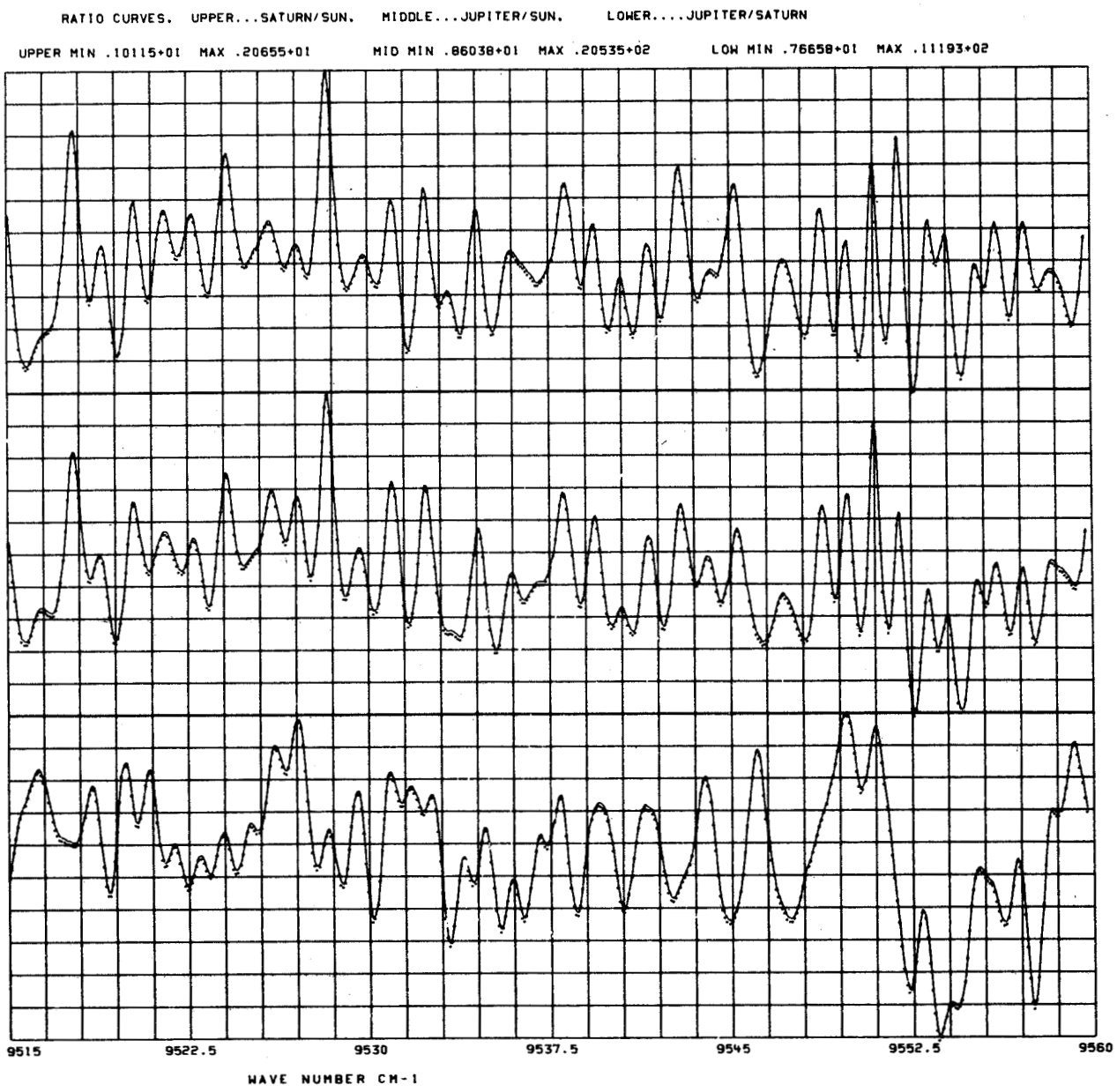

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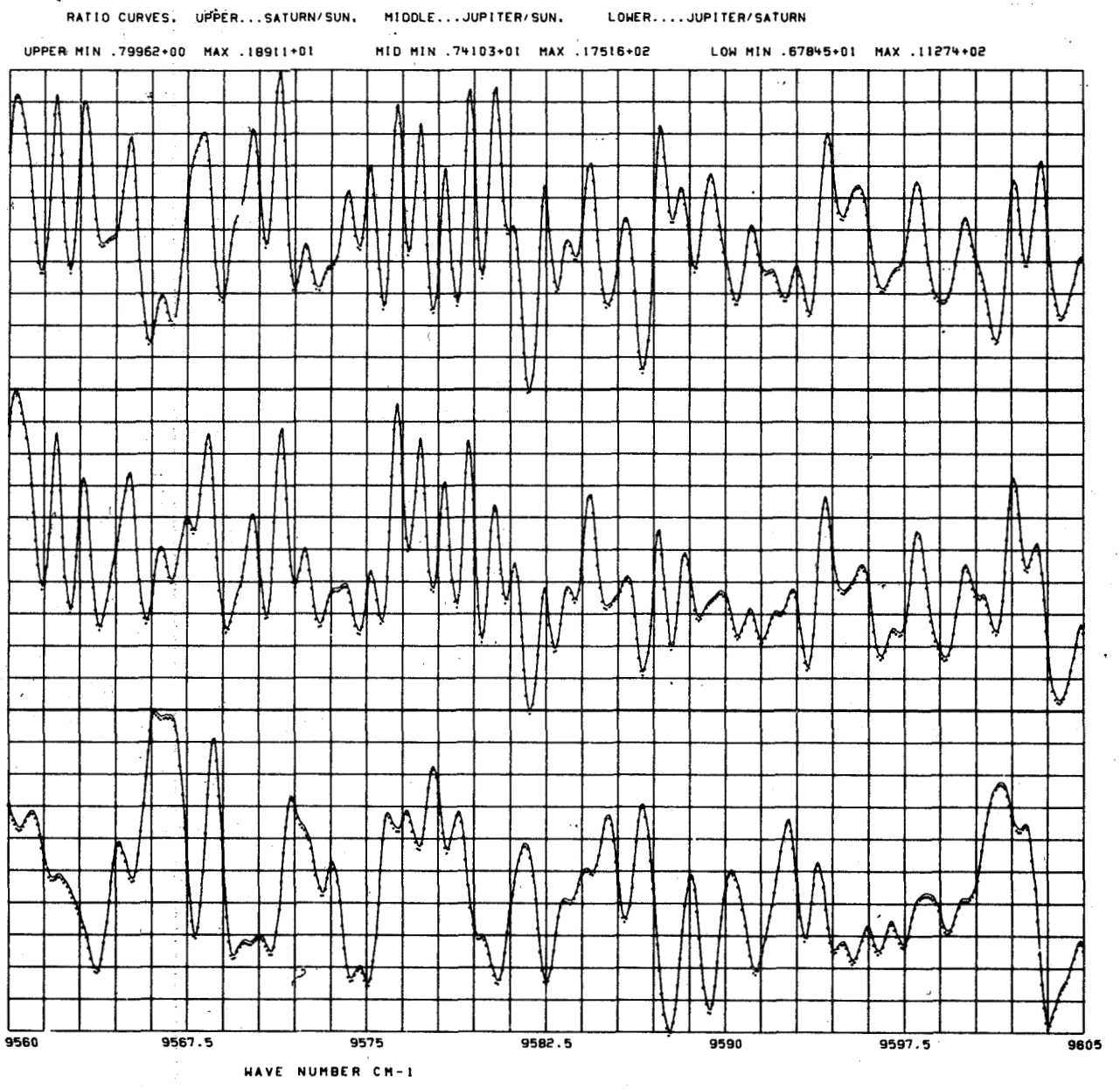

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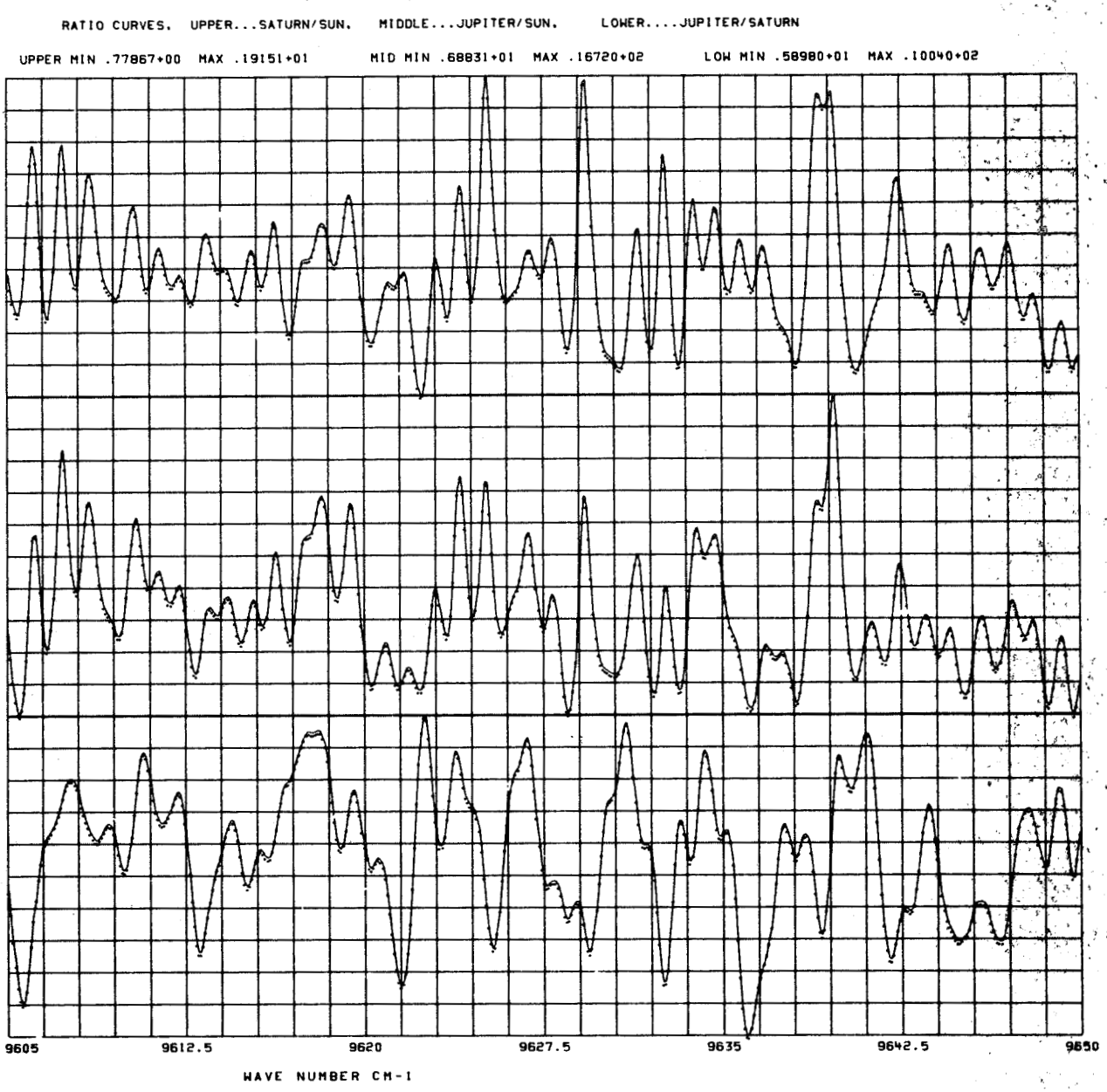

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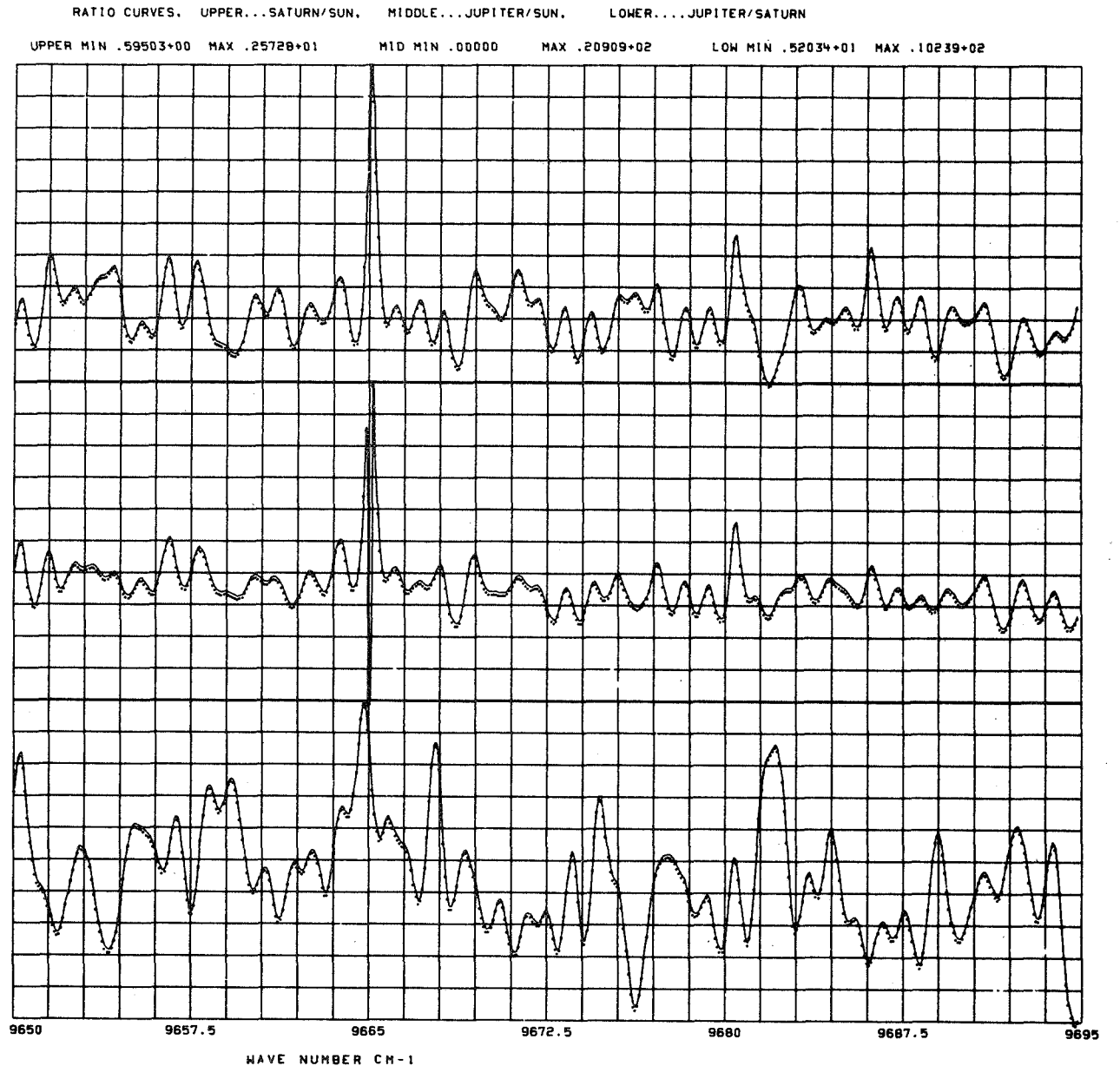

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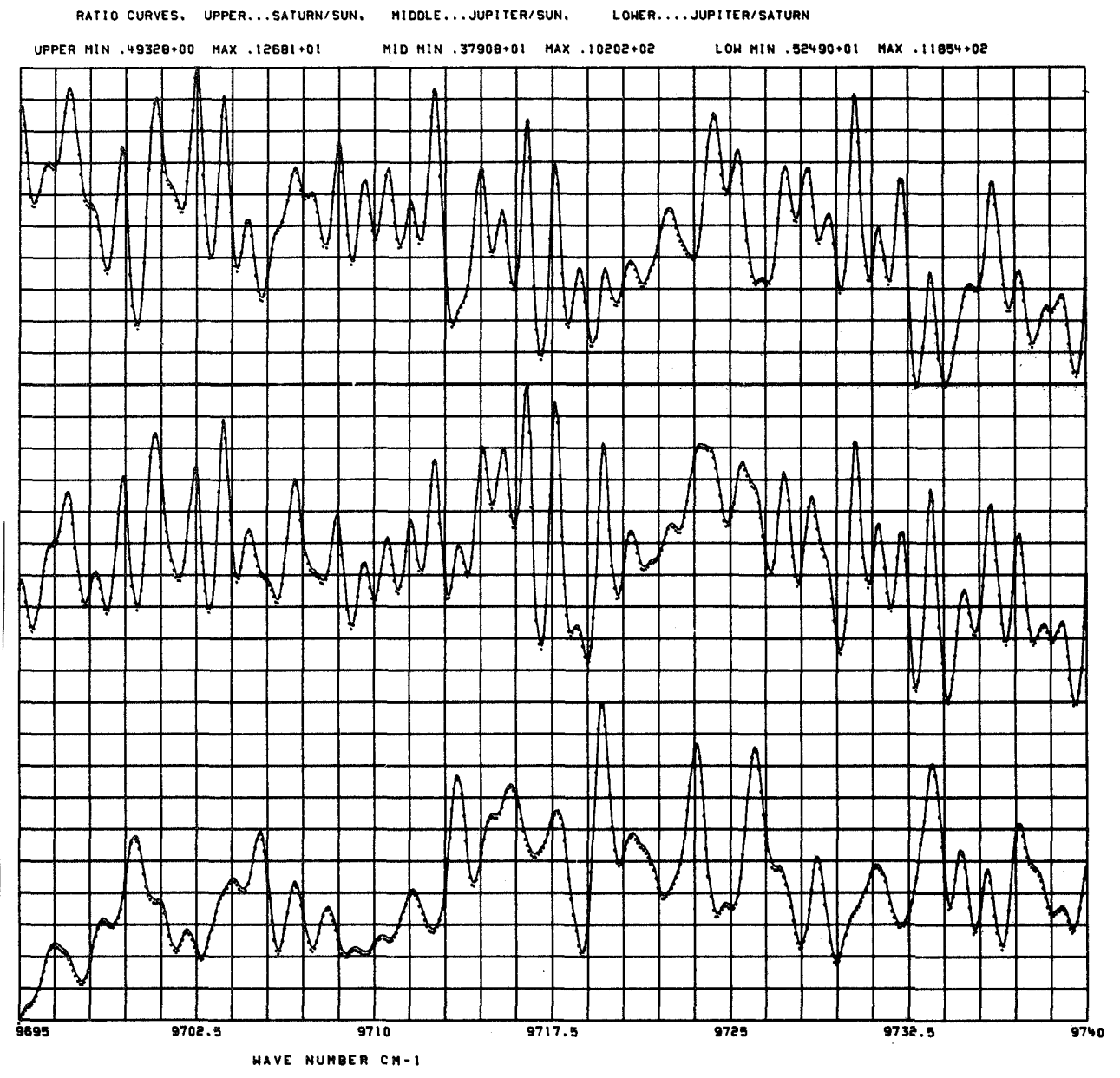

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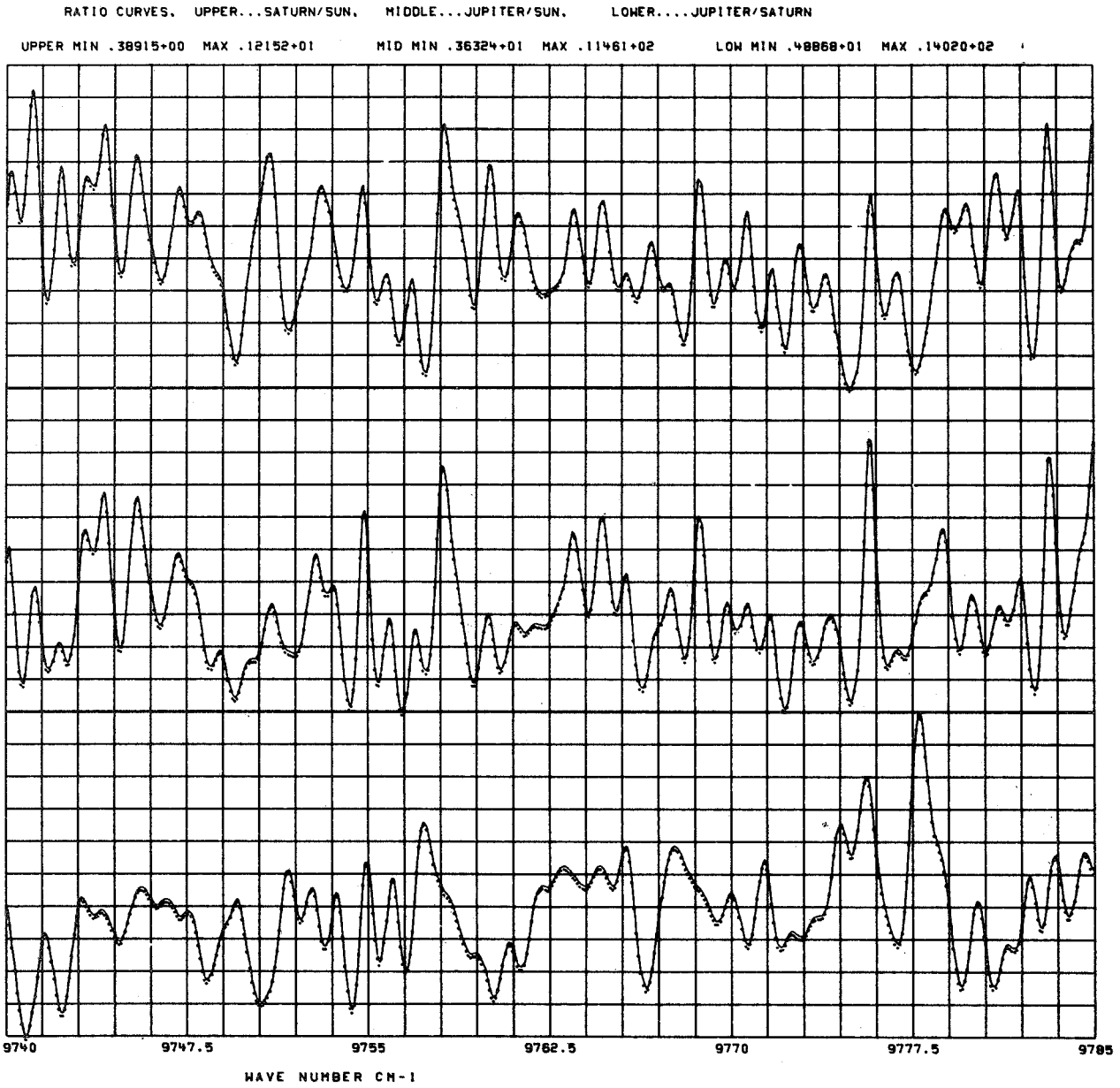

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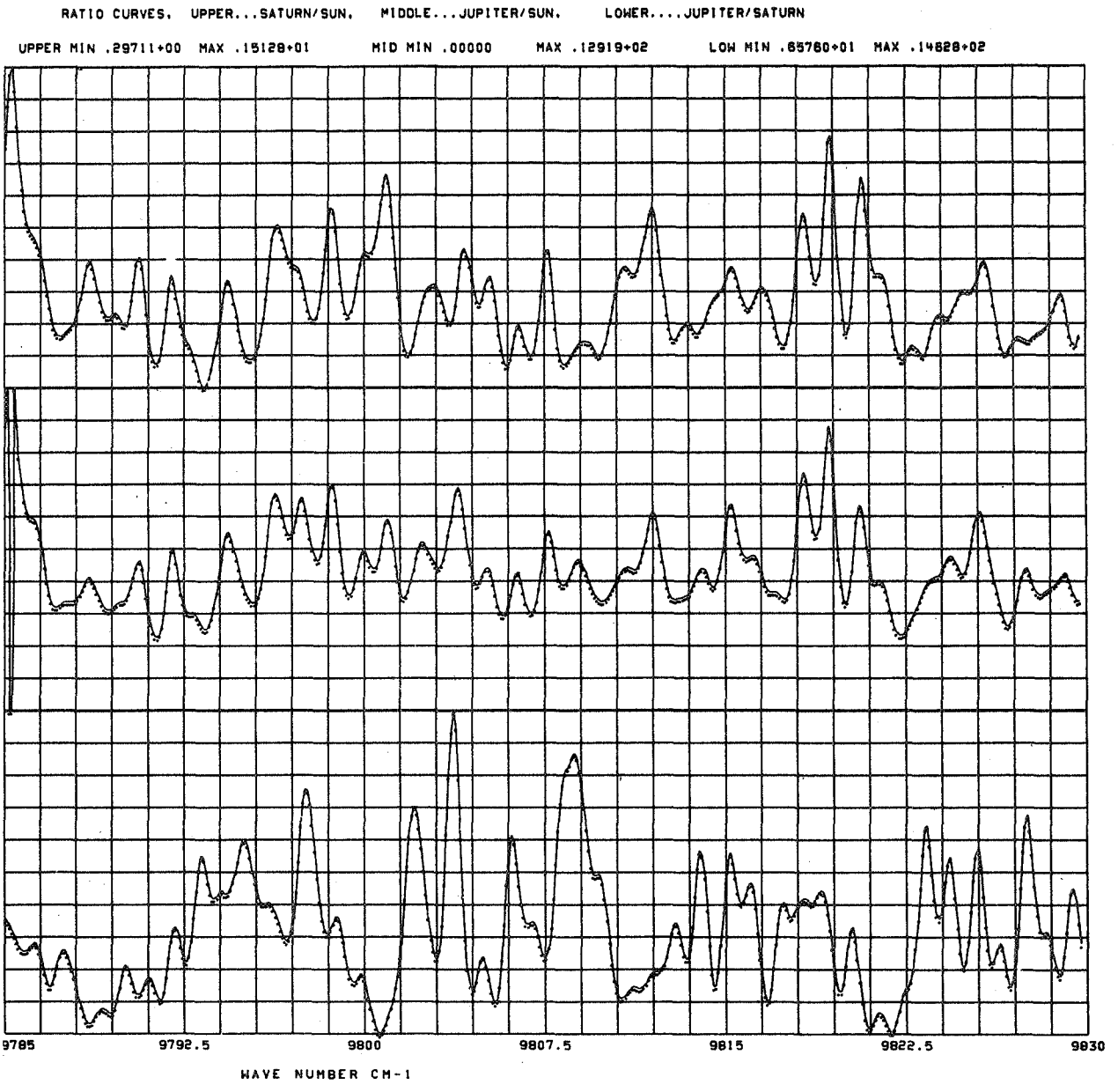

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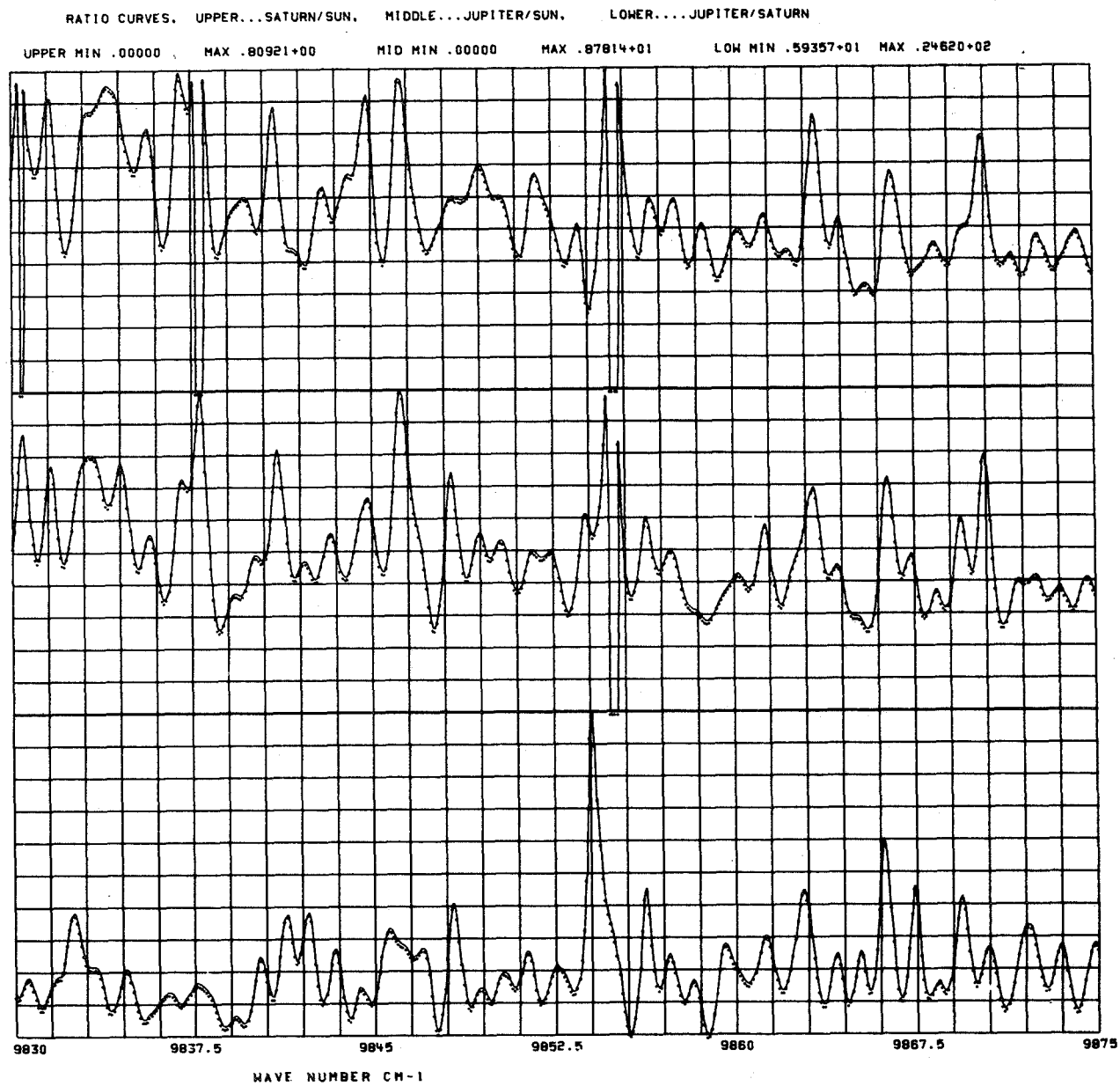

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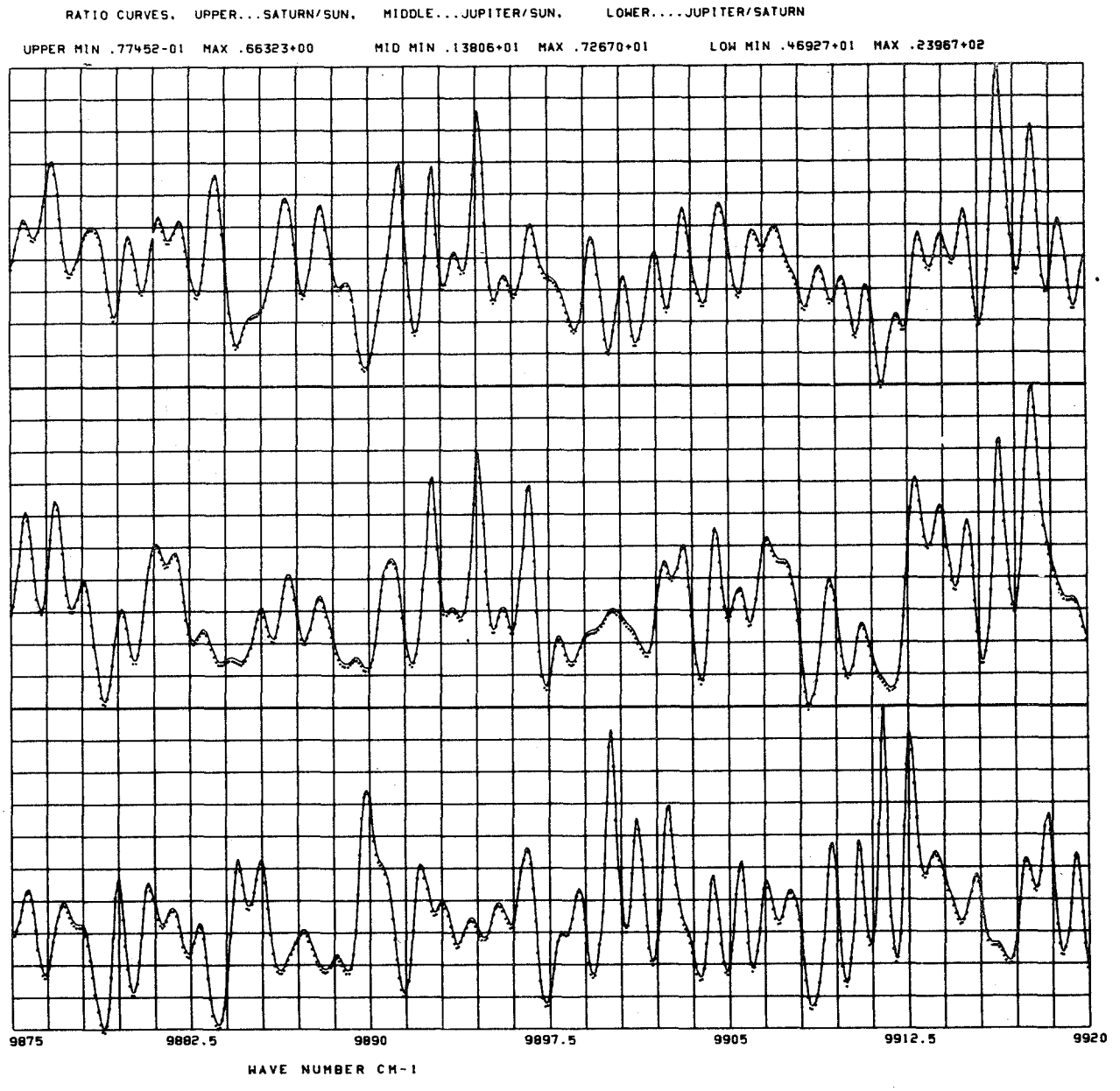

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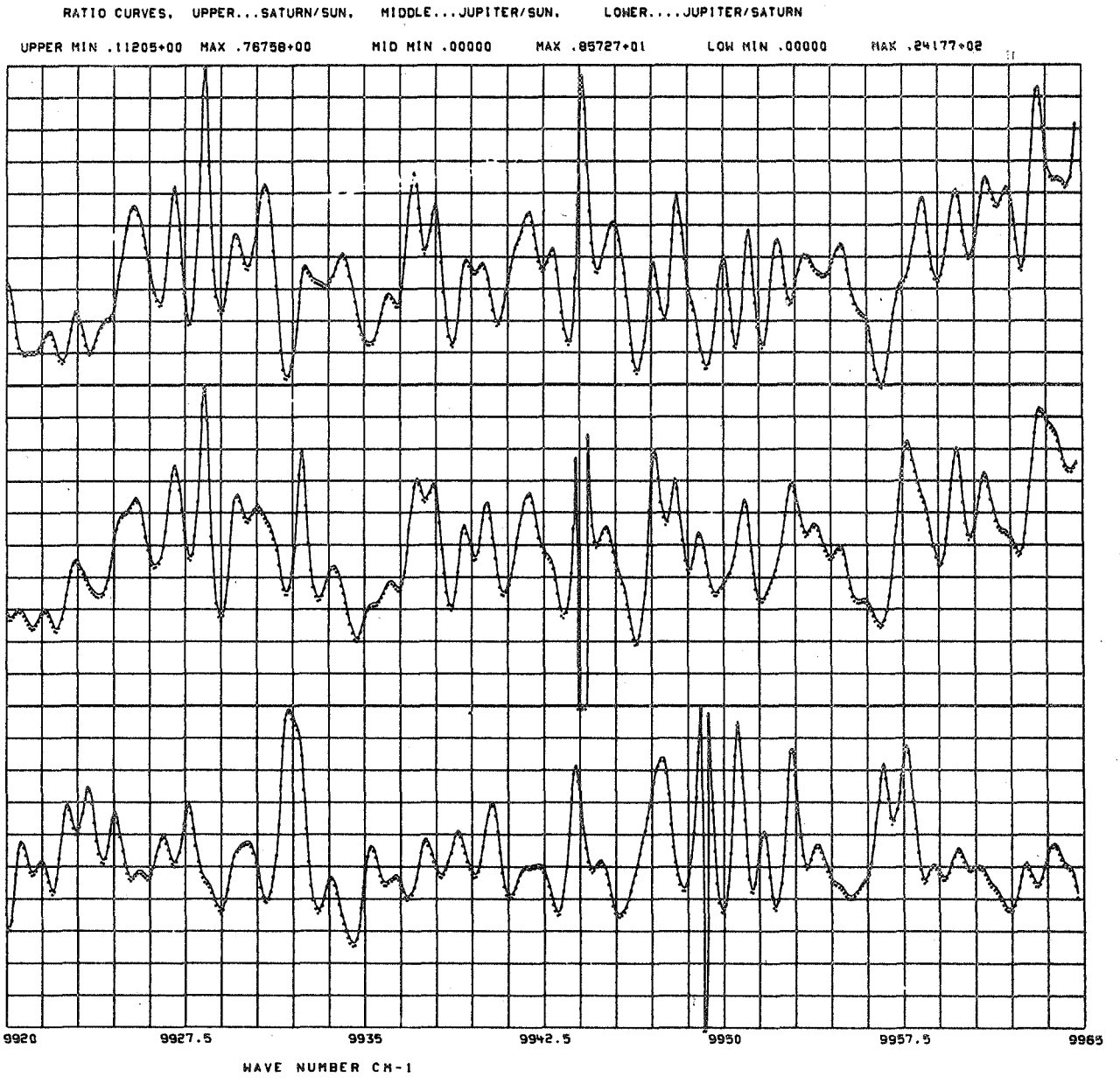

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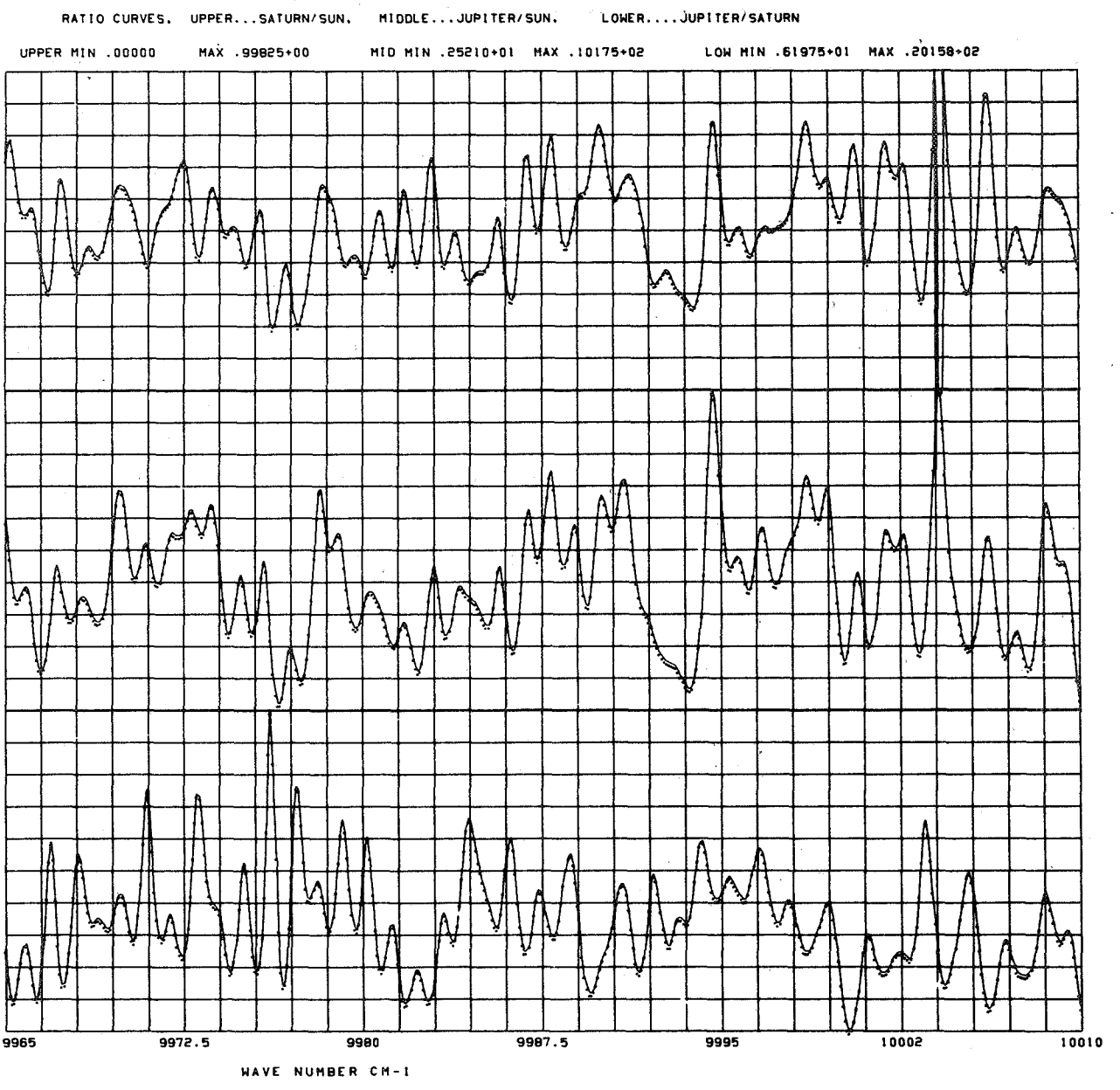
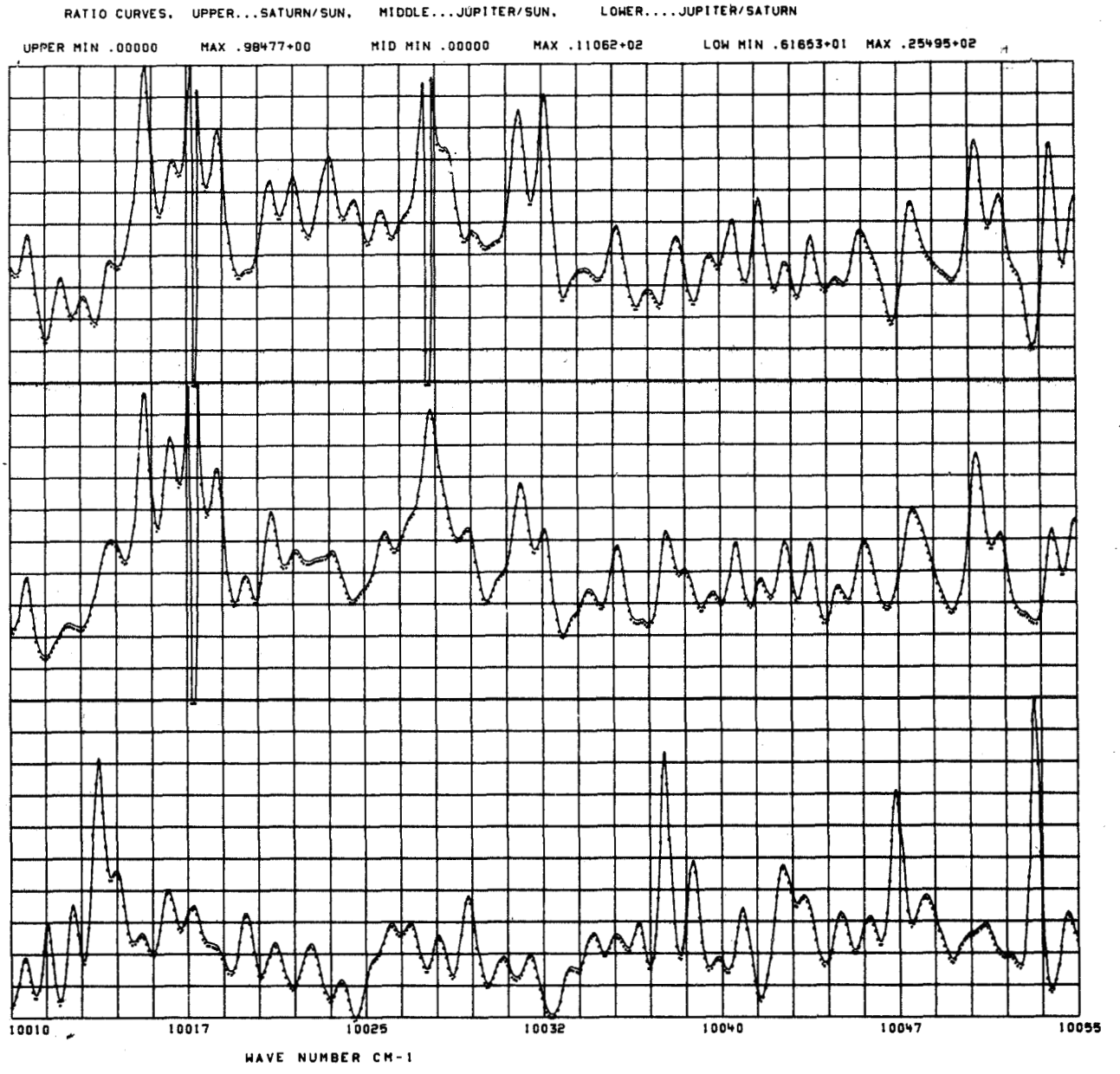


Figure 4 (*continued*).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.



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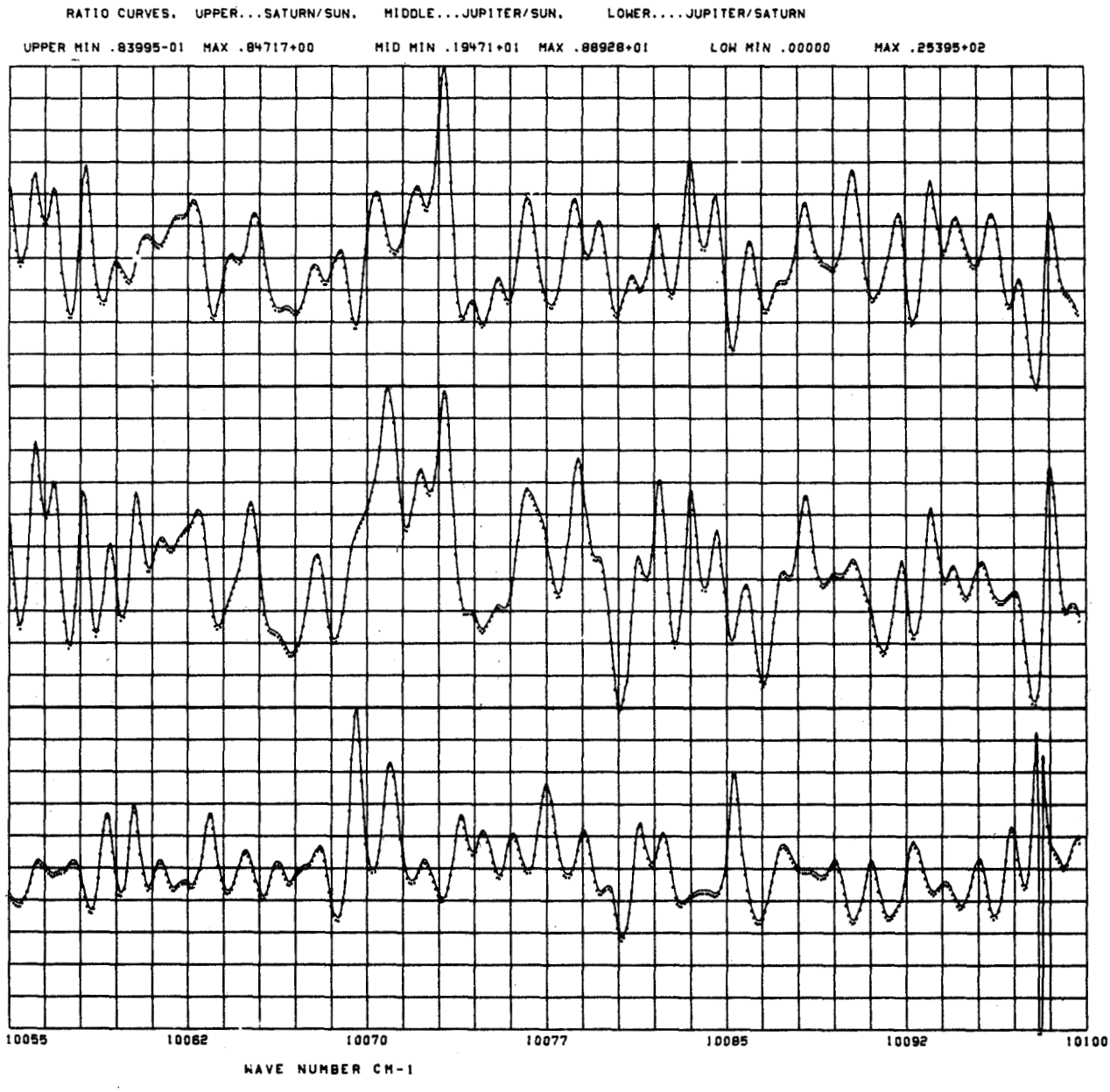

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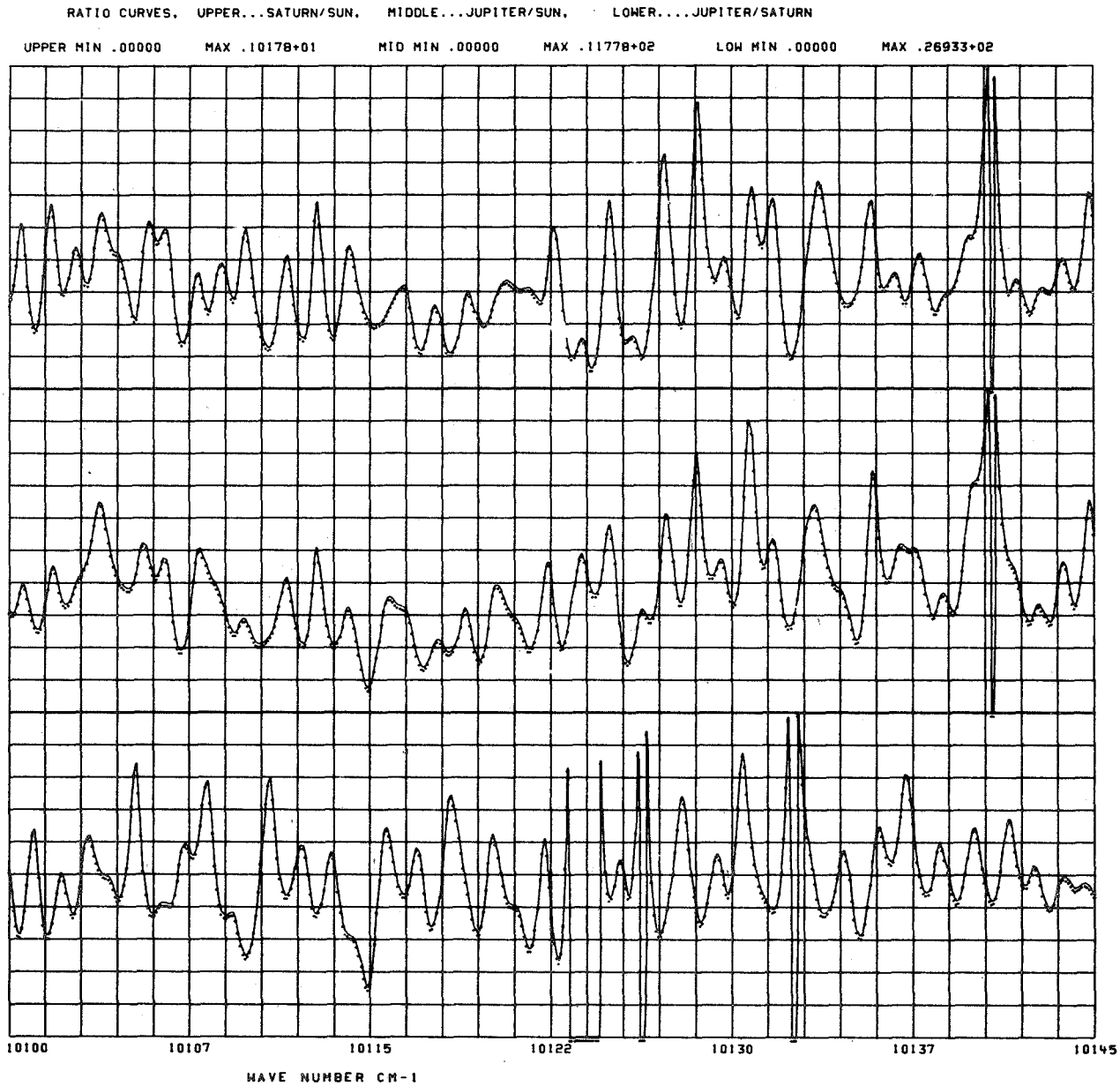

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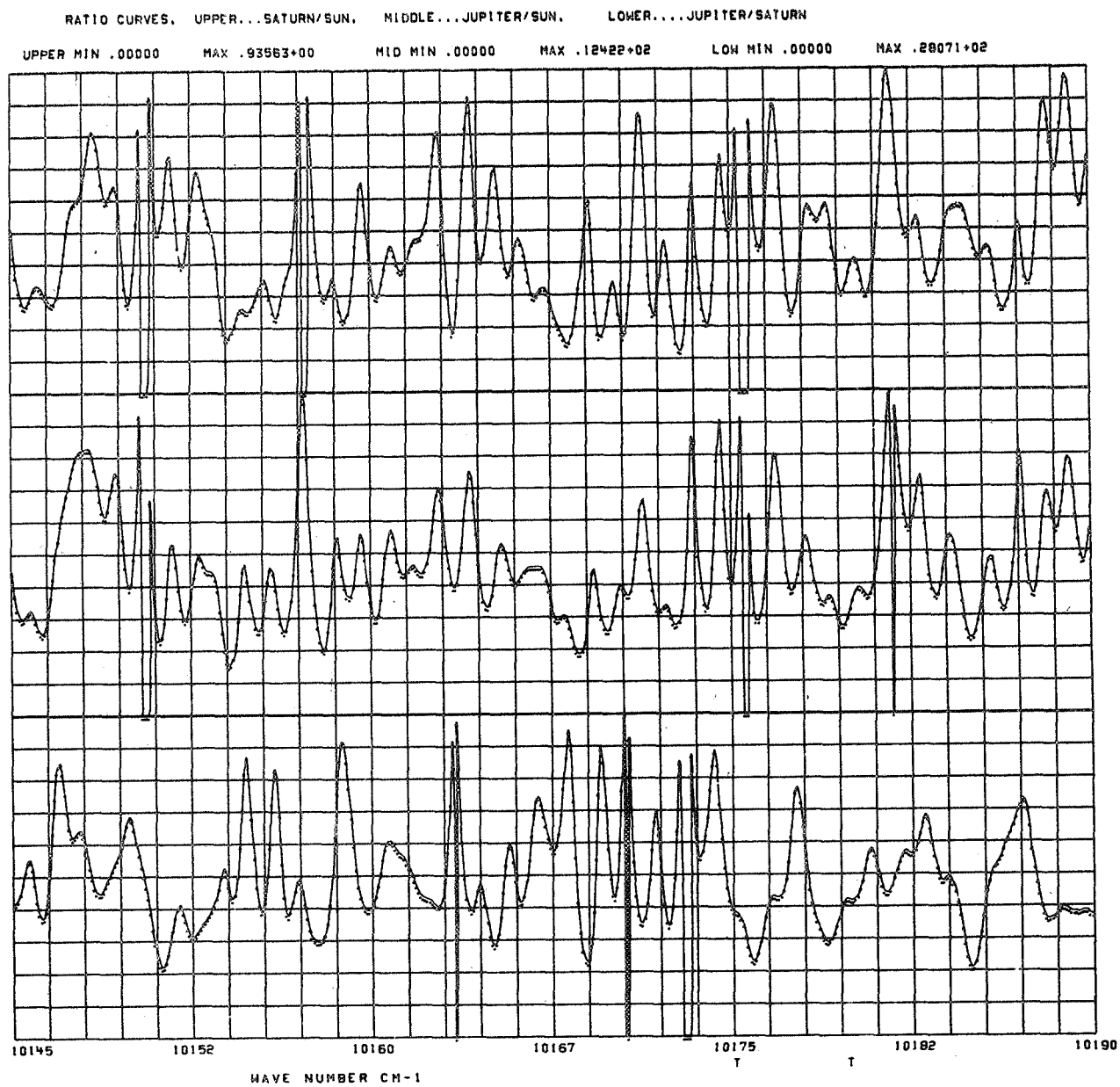

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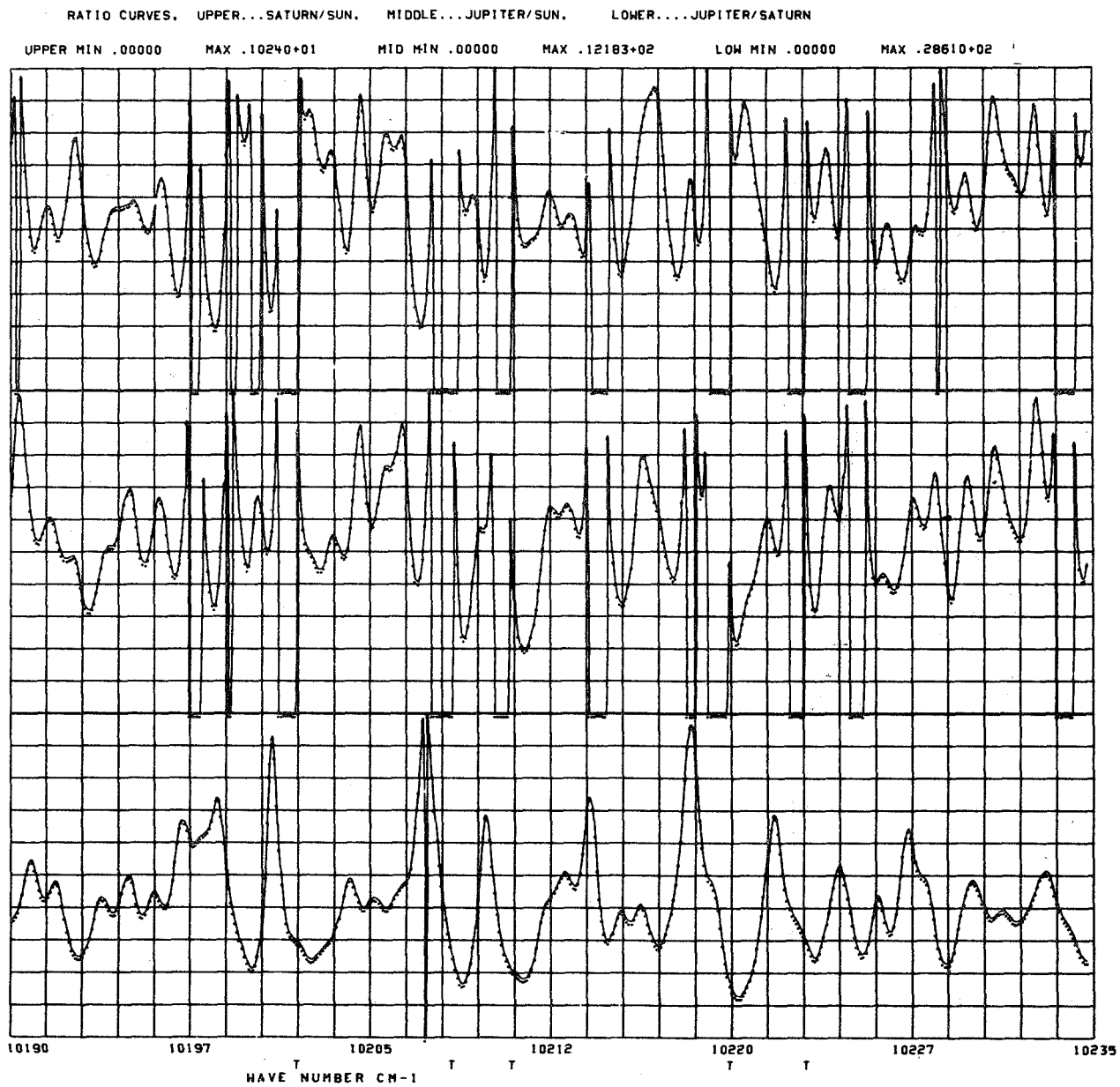

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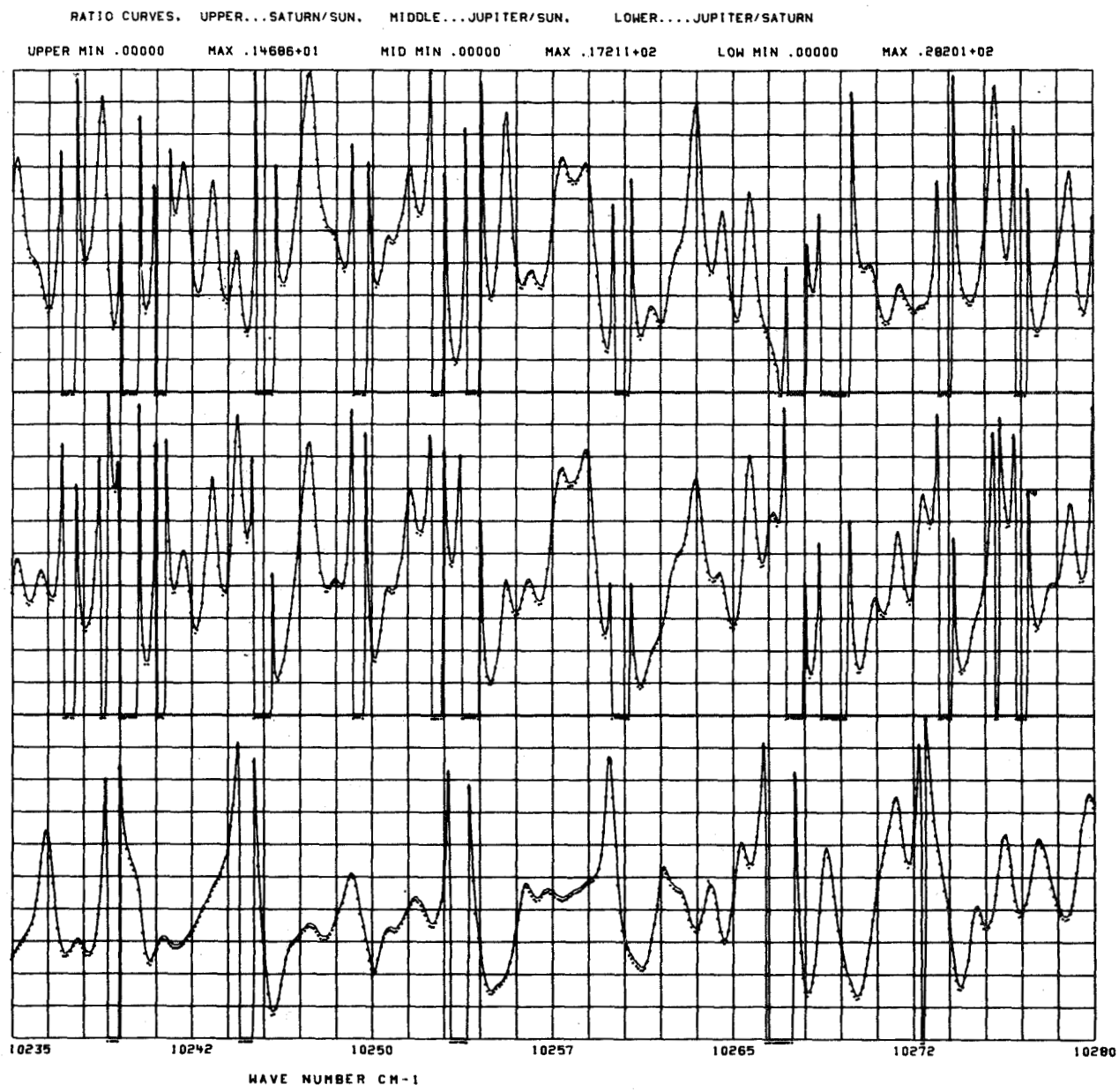


Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

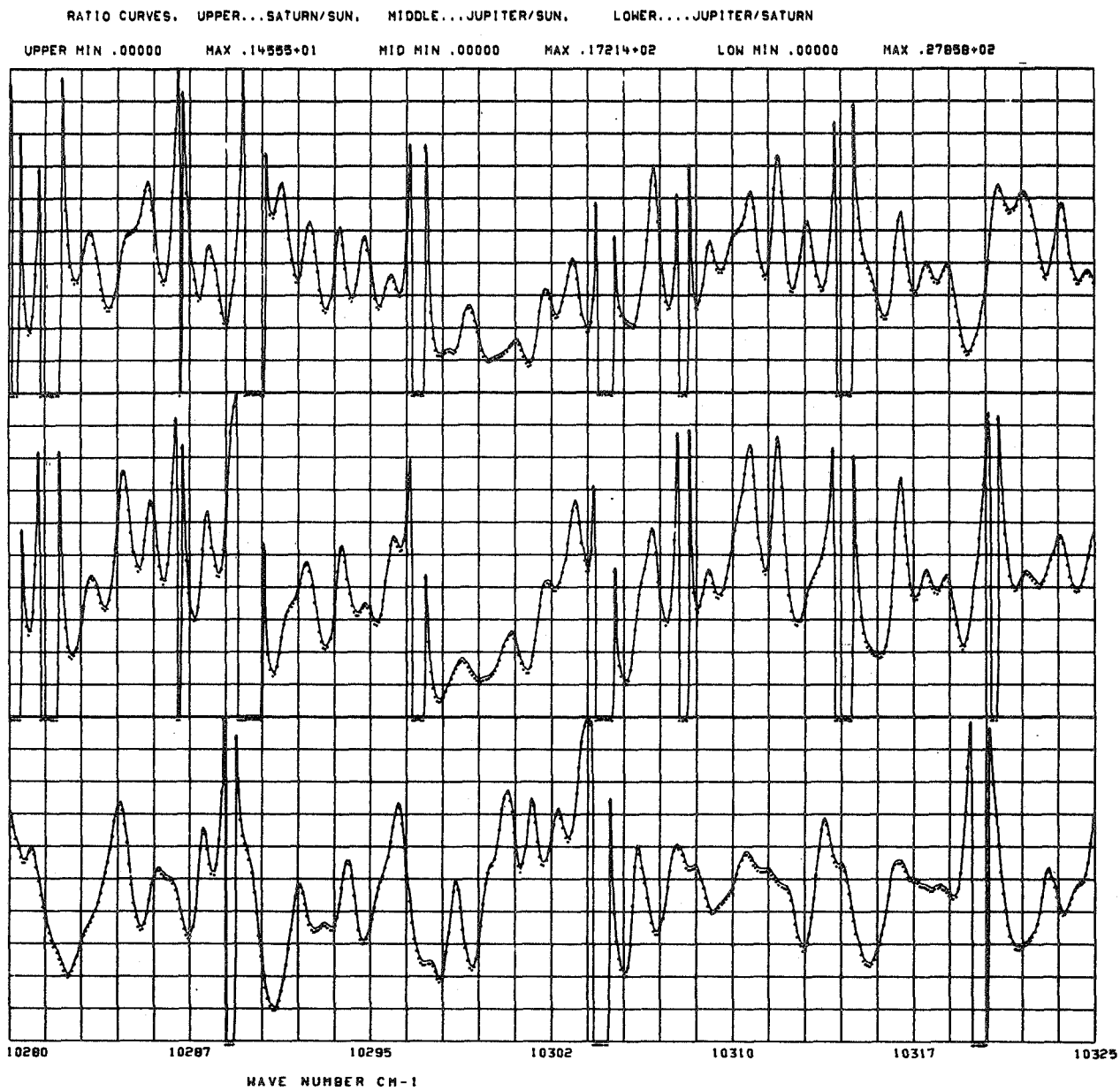


Figure 4 (continued).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

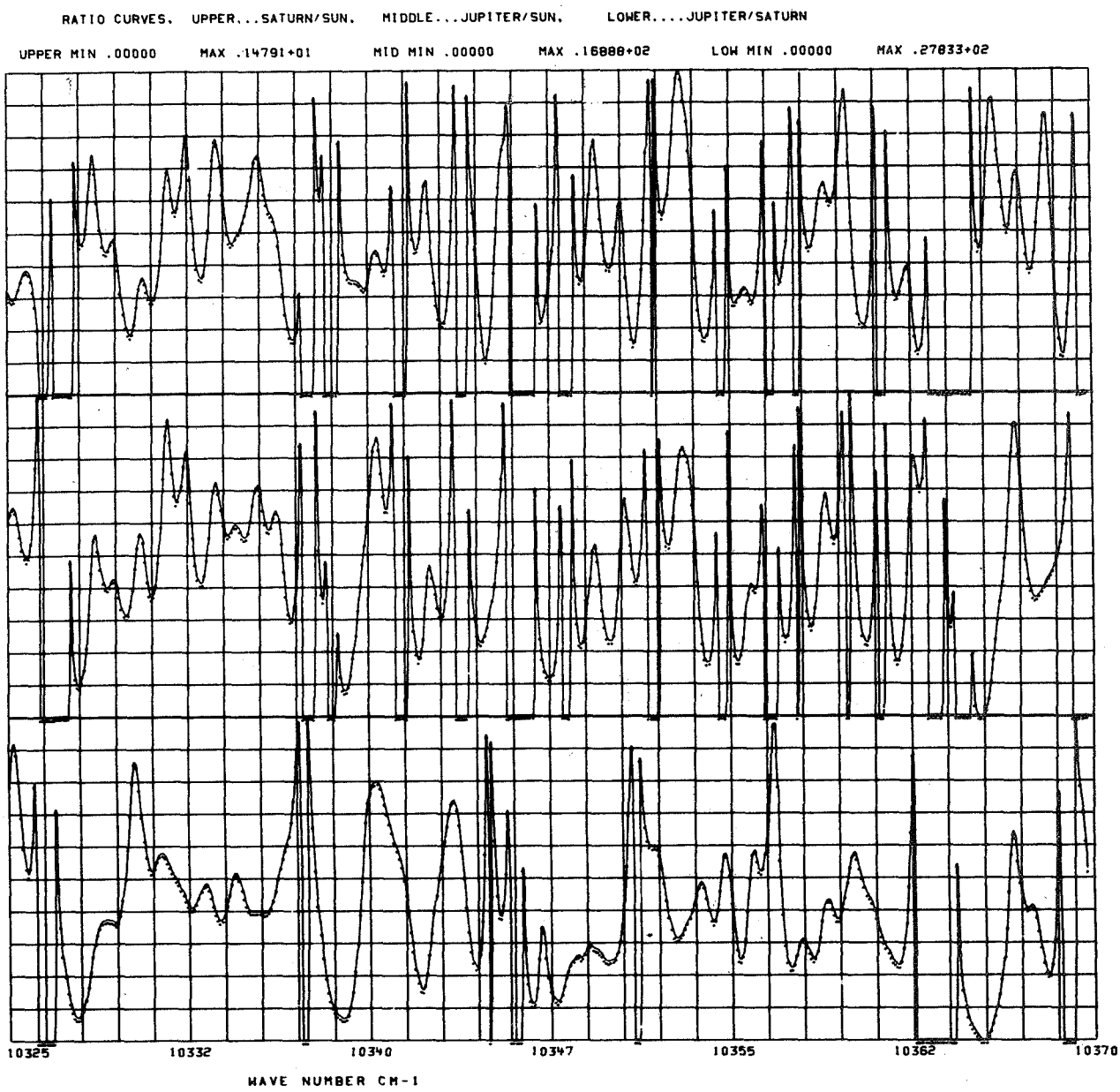
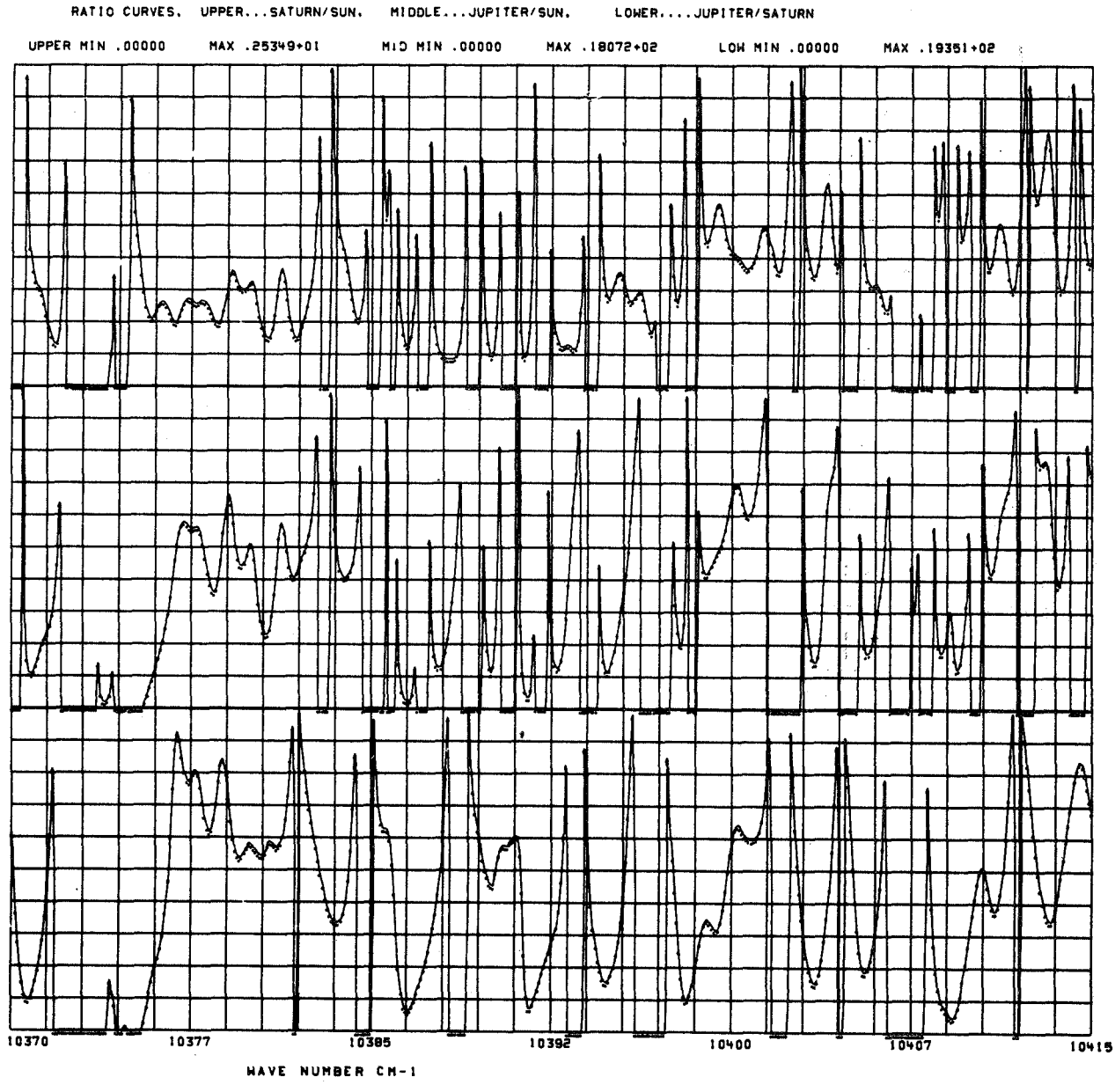


Figure 4 (continued).—Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.



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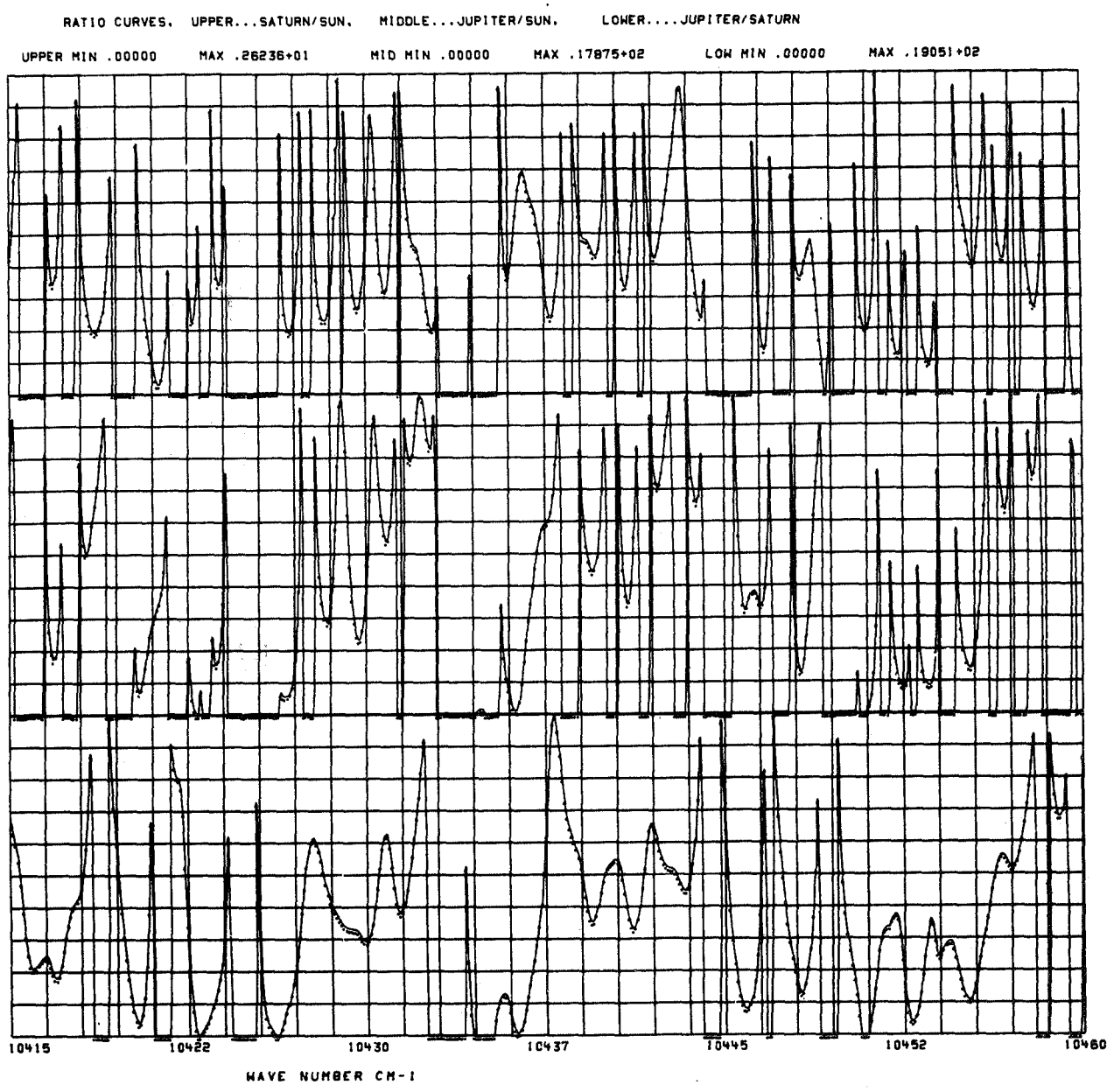

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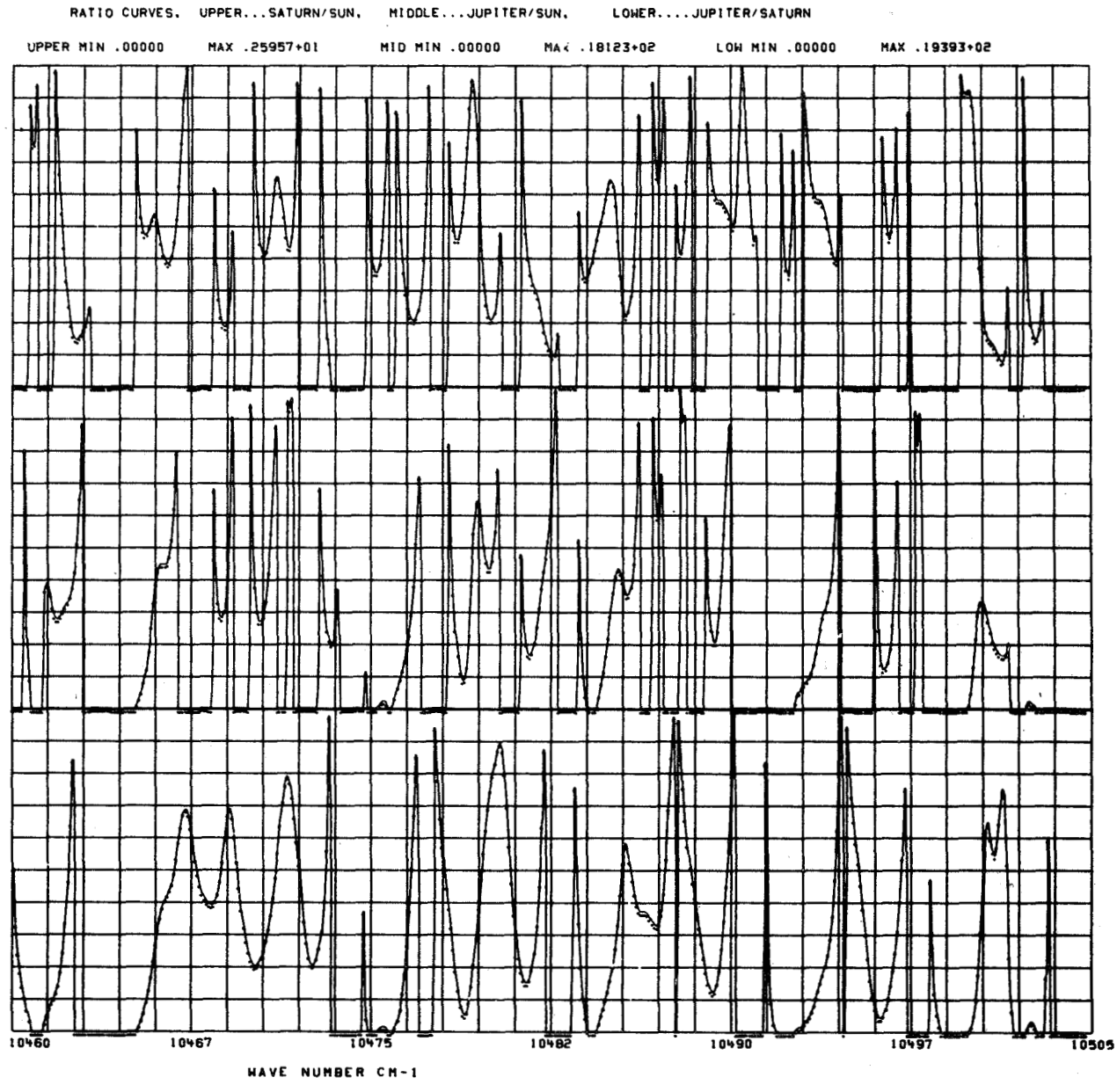

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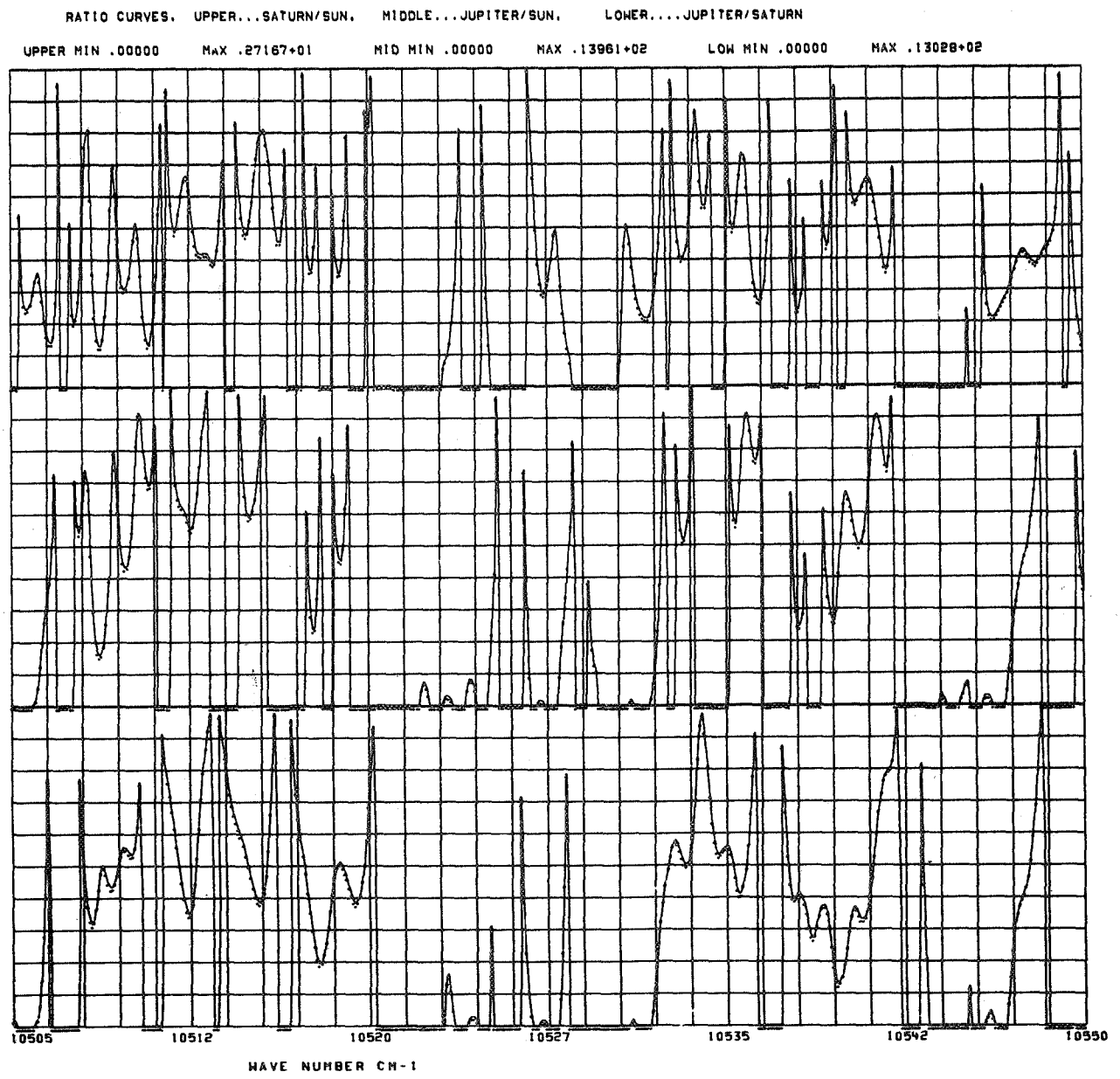

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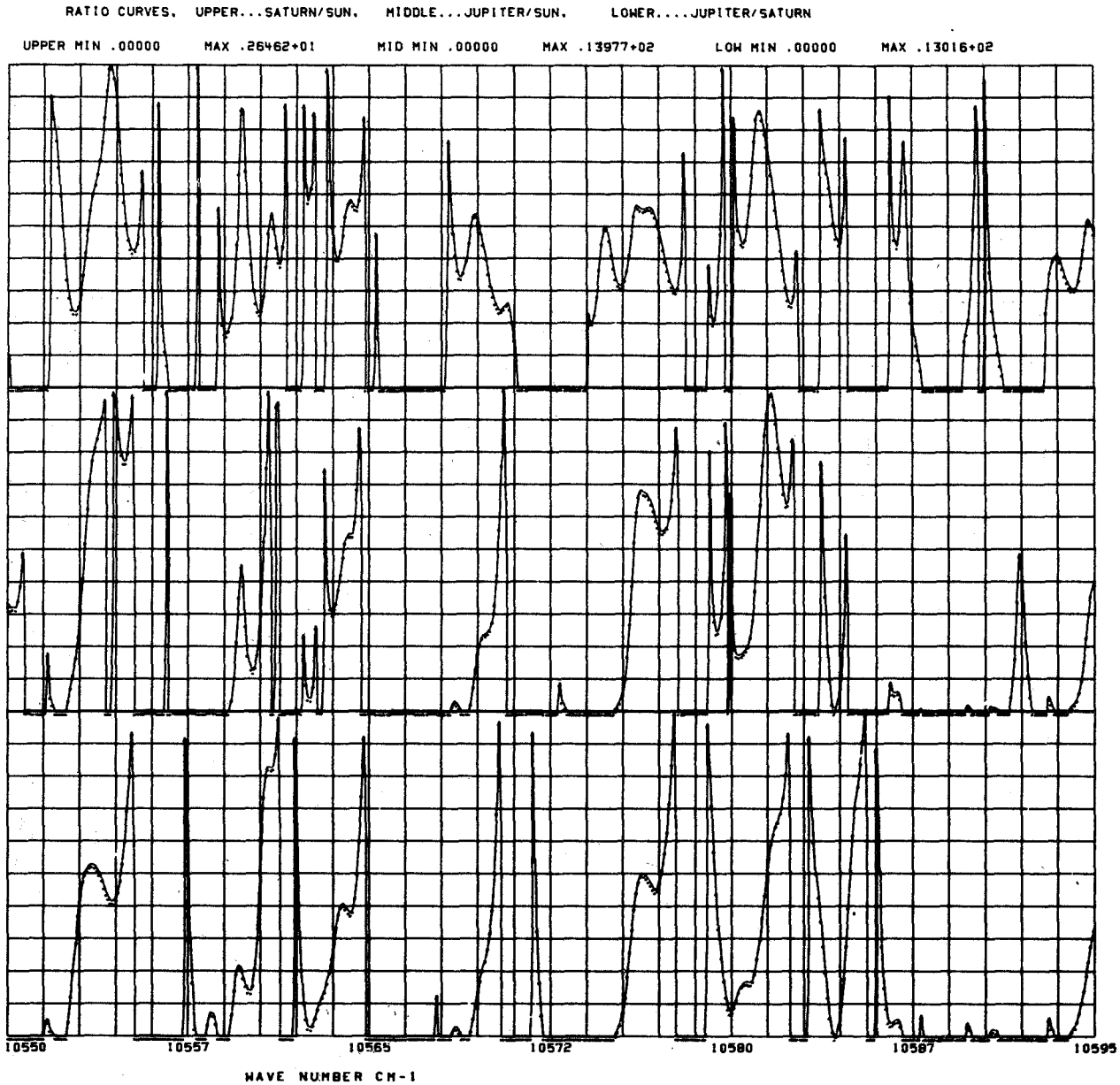

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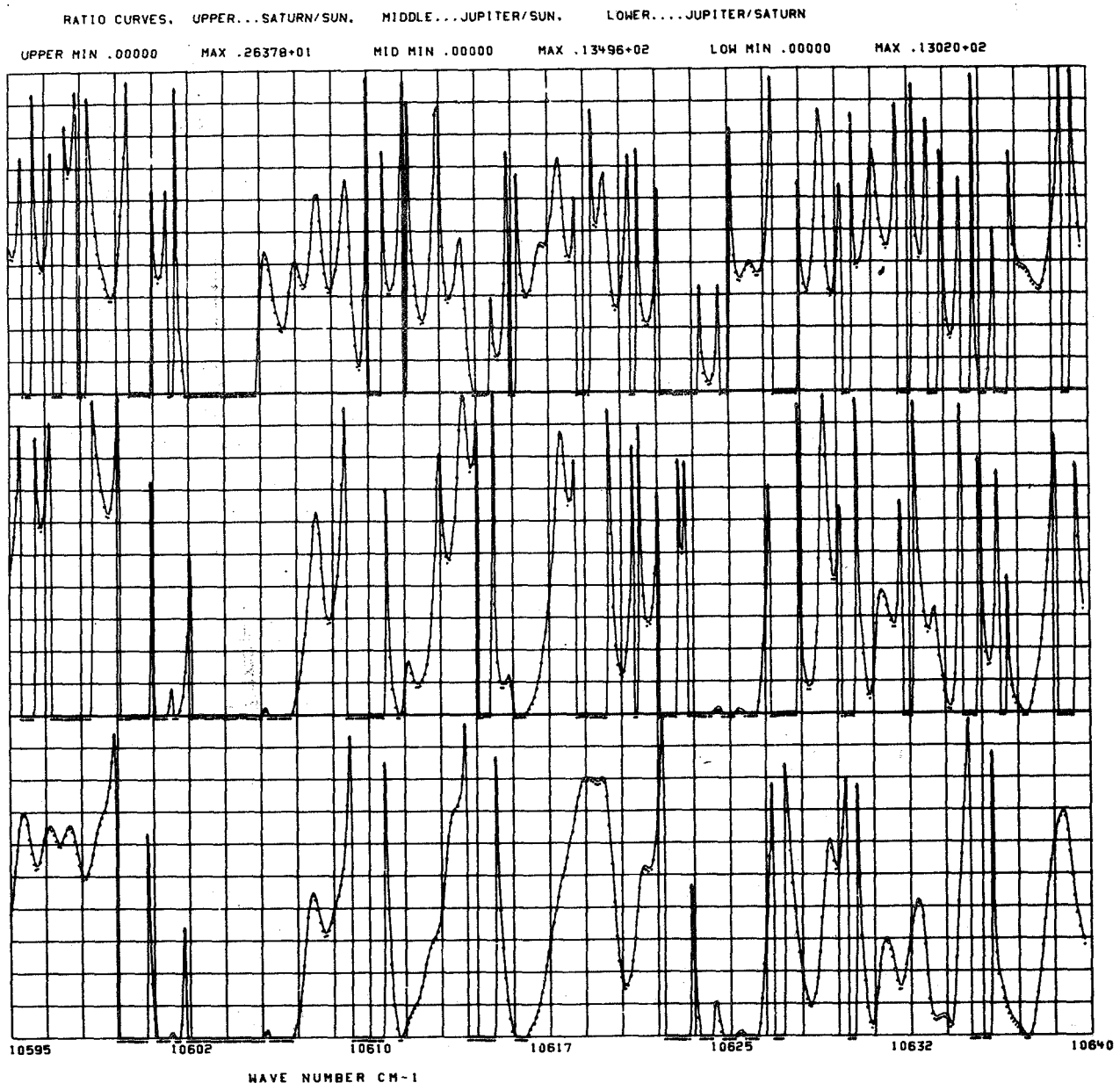

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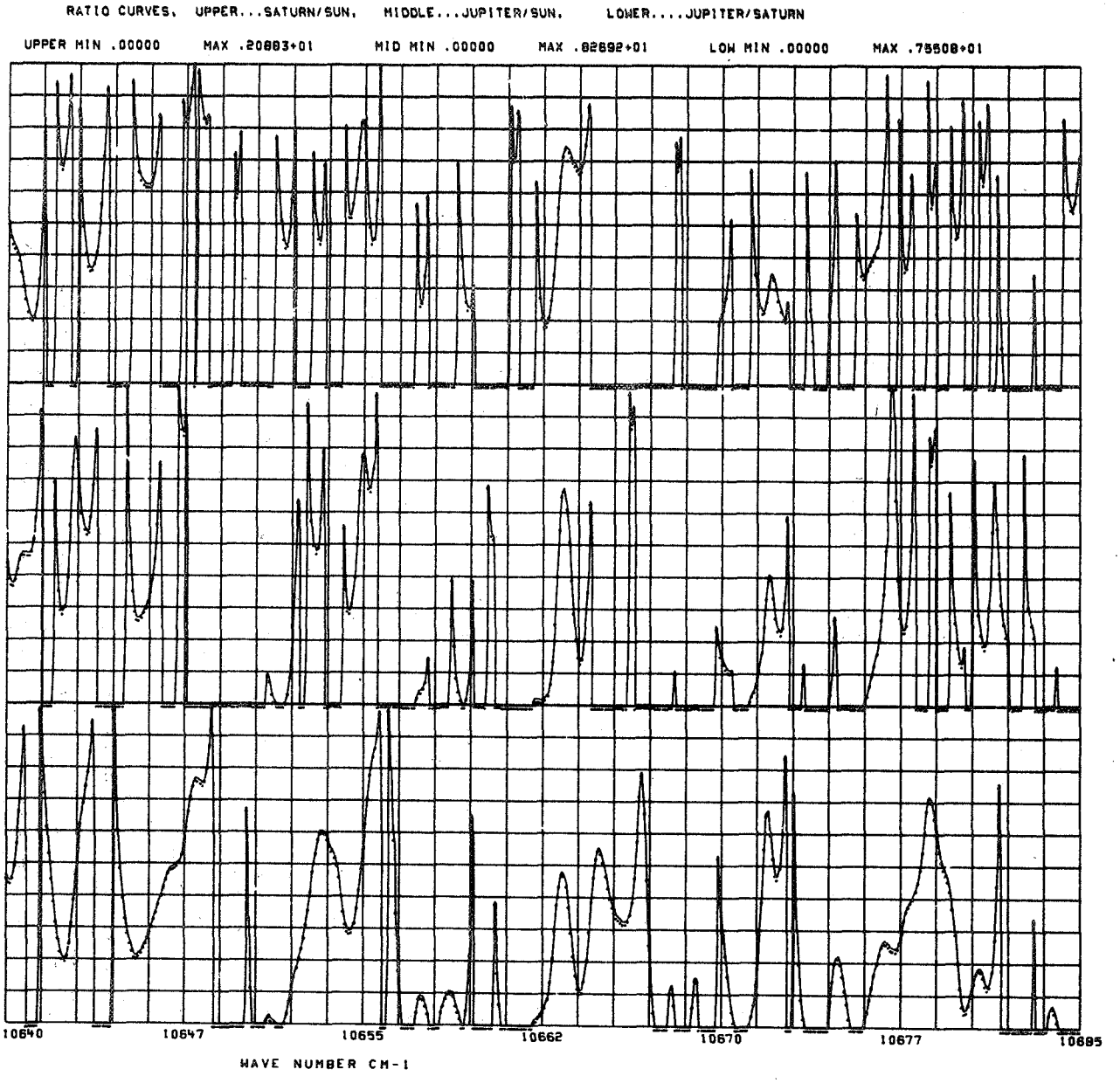

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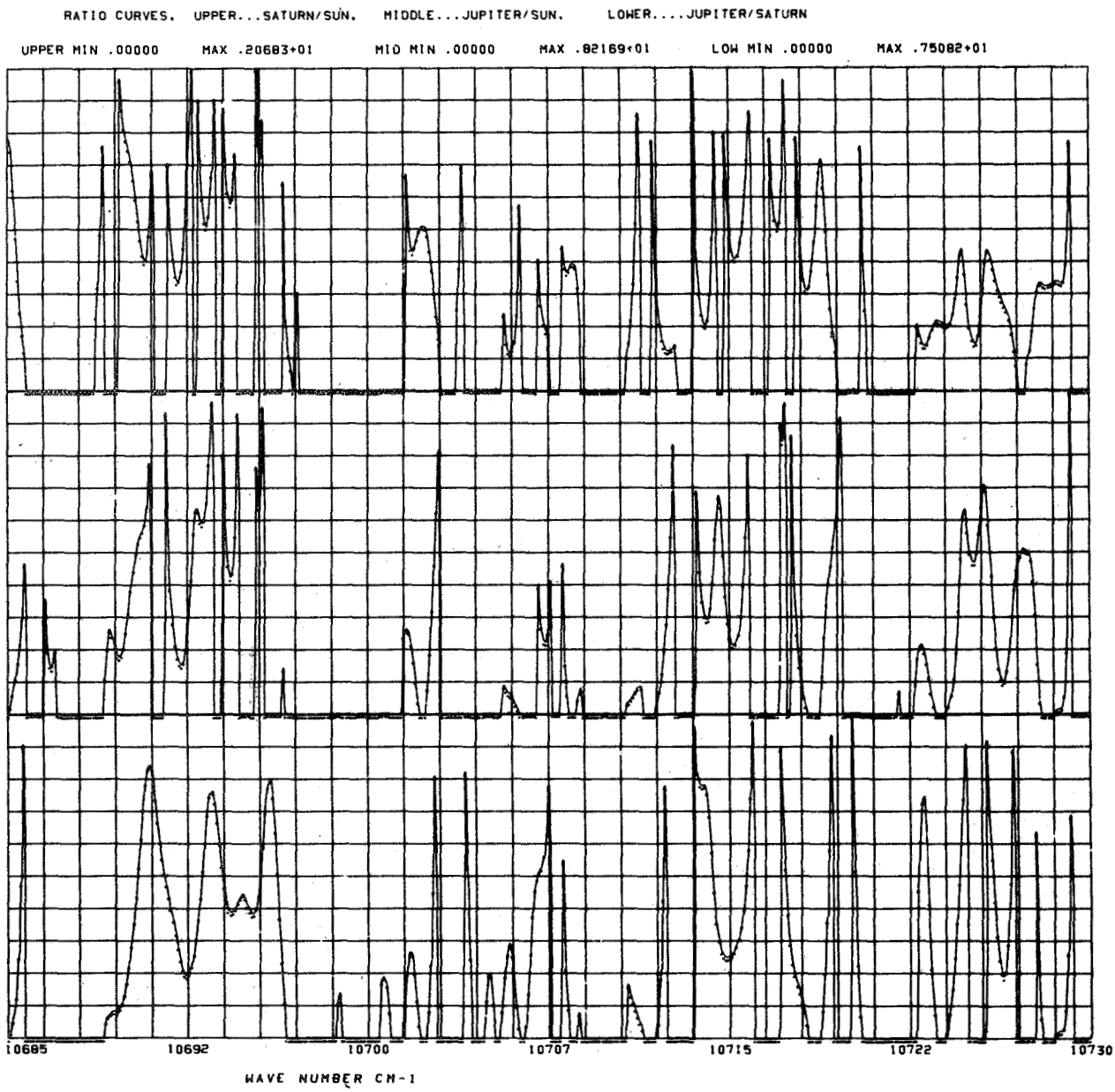

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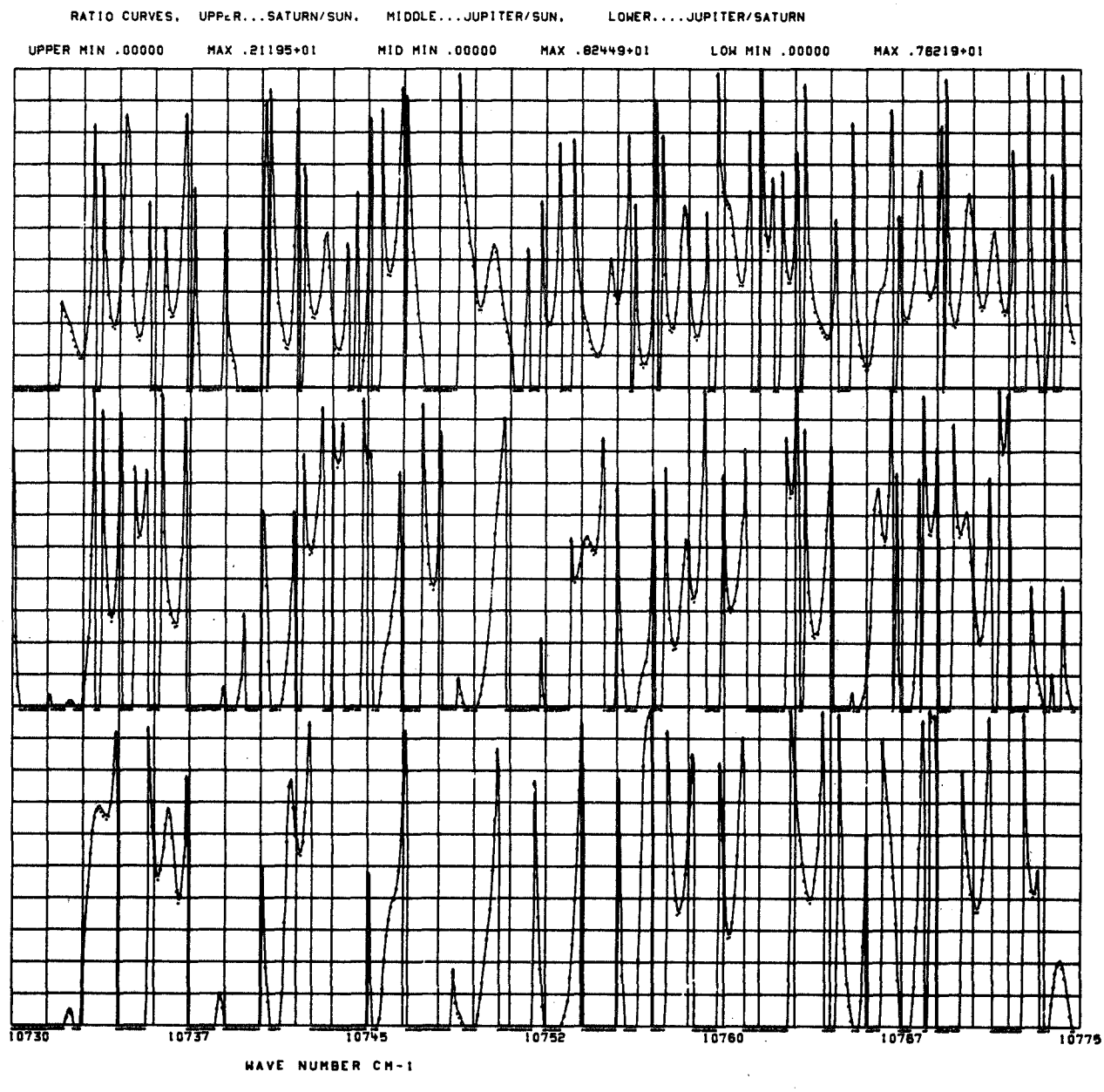

Figure 4 (concluded).–Ratio plots of Saturn and the Sun, Jupiter and the Sun, and Jupiter and Saturn spectra compared at a resolution of 0.5 cm^{-1}.

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16. Abstract

Near-infrared spectra of Jupiter, Saturn, and Uranus were measured at resolutions higher than previously available in the range from 6000 to 10 750 cm^{-1}. For Jupiter and Saturn, this resolution was 0.5 cm^{-1}; for Uranus, it was 32 cm^{-1}. The spectra are presented both individually and as ratio spectra, in which the planetary spectra are divided by the solar spectrum. The Uranus spectrum is shown with Saturn, Jupiter, and Sun spectra reduced to the same resolution so that Uranus can be compared with the other outer planets. The high-resolution Saturn, Jupiter, and Sun spectra are presented in parallel plots to simplify comparisons between them.

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