OBSERVATIONS OF THE 1991 ECLIPSE AT 3.5 mm WAVELENGTH

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Abstract. We report preliminary results of the partial eclipse seen from the BIMA millimeter–wavelength interferometer in northern California. The use of an interferometer has many advantages over previous single–dish eclipse observations at 3 mm, and in particular it allows a quite different type of measurement of the height of the "3-mm limb" which is direct and precise : we find it to be 11.9″ ± 0.4″ above the optical limb.

Key words: eclipses – techniques: interferometric – Sun: radio radiation

1. Introduction

At millimeter wavelengths, as in other wavelength ranges, solar eclipses have long been recognized as providing a means to carry out otherwise–impossible investigations of the Sun's atmosphere. In particular, the motion of the Moon's limb can be used to provide higher spatial resolution than a millimeter telescope can achieve alone. Since the typical resolution of single–dish telescopes operating at 3 mm wavelength is not great (1.1′ for a 10-m telescope; 15″ for the Nobeyama 46-m telescope), it is important to make use of any opportunities for better spatial resolution. During an eclipse we can achieve this by using the fact that the difference between two successive measurements made while the Moon is moving across the Sun represents the flux from a narrow strip whose width equals the distance moved by the Moon in the corresponding interval. Since typically the Moon moves at 0.5″ per second, then a 1 second integration time can produce subarcsecond resolution in the direction of the Moon's motion.

Within the last few years the intrinsic resolution achievable at millimeter wavelengths has improved enormously through the development of millimeter-wavelength interferometers. Information on arcsecond–scale structures in flares is now readily available (Kundu *et al.*, 1990; White *et al.*, 1992). However, the Sun is so complex and constantly changing that true imaging is still difficult with the 3–element interferometers presently available. Thus the structure of the quiet-Sun atmosphere has not yet been thoroughly studied with arcsecond resolution, and eclipse observations are still important for such studies.

We observed the 1991 July 11 eclipse with the 3–element Berkeley-Illinois-Maryland Array (BIMA) in northern California at 3.5 mm wavelength. Seen from this location, the Moon obscured half the solar disk. However, since the field of view of the telescope is about 2′ there is little one can do with a total eclipse that cannot also be achieved in a partial eclipse. Here we report the results of a preliminary analysis of the BIMA observations. We focus mainly on the height of the "3-mm limb", since the use of an interferometer provides a quite different means for measuring this quantity, which proves to be very precise and much less dependent on model comparisons.

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2. The Observations

BIMA consists of three 6-m dishes operating as an interferometer in the 70–115 GHz frequency range. It is important to bear in mind some aspects of interferometers in interpreting these observations. Each pair of antennas provides an interferometer pair, and the output of each interferometer pair is a one-dimensional spatial Fourier transform of the brightness distribution within the primary beam of each 6-m dish (2.3′). Two sidebands at 86 GHz and 89 GHz were the observing frequencies. The fringe spacing and orientation of the Fourier pattern on the sky are determined by the locations of the two antennas: for these observations the 3 BIMA antennas were at locations 12.2 m W, 12.2 m N and 30.5 m N of the array center. The resulting baselines provided fringe spacings typically of 40″, 40″ and 20″, with differing orientations. The interferometer measures both an amplitude and a phase. If there is a single source dominating the flux in the field of view, the phase is a measure of its location (in one dimension) relative to the center of the field of view; if the source is moving, the phase will change by 360° as the source moves a distance corresponding to one fringe spacing in the appropriate direction. This is important, as we show below. Solar observations with BIMA are described more fully by White and Kundu (1992).

3. First Contact

First contact occurred at 17:18 UT at a position angle of 253° (measured east around the solar circumference from celestial north). The geometry of the eclipse is very similar to the figure shown by Belkora *et al.* (1992) for the Owens Valley observatory, except that Hat Creek is further north and first contact accordingly occurred further south on the Sun's west limb. The Moon's velocity vector relative to the Sun at the time was (0.48″ s^{-1}, –0.09″ s^{-1}) in RA and Dec., respectively. The projected component along the normal to the Moon's surface at the point of contact was 0.44″ s^{-1}. The time resolution of the BIMA observations was 0.4 s, so the intrinsic spatial resolution was 0.2″ in the direction of motion.

The curvature of the Moon's limb across the field of view of the BIMA dishes was only 2.3″, so to a good approximation both it and the Sun's limb can be regarded as straight edges (given that the fringe spacing to be used was 40″). The limbs are nearly vertical on the sky during first contact. For such an arrangement, an east-west baseline gives optimal results because the sharp edge in the brightness distribution at the solar limb is parallel to the (north-south) fringes and produces a strong response in the interferometer. At first contact the baseline formed from antennas 1 and 2 was the most east-west of the baselines, with an effective EW fringe spacing of 51″ and NS fringe spacing of 95″; the position angle of the fringes is therefore 242°, compared with 252° for the limbs.

The observation of first contact on baseline 12 at 89 GHz is shown in Figure 1. The three curves are the correlated amplitude (solid line) and phase (dots) measured by the interferometer pair, as well as the total power (solid line; arbitrary units) measured by one of the telescopes acting as a single dish. The amplitude and total power plots have both been smoothed with a 4-second boxcar; however,

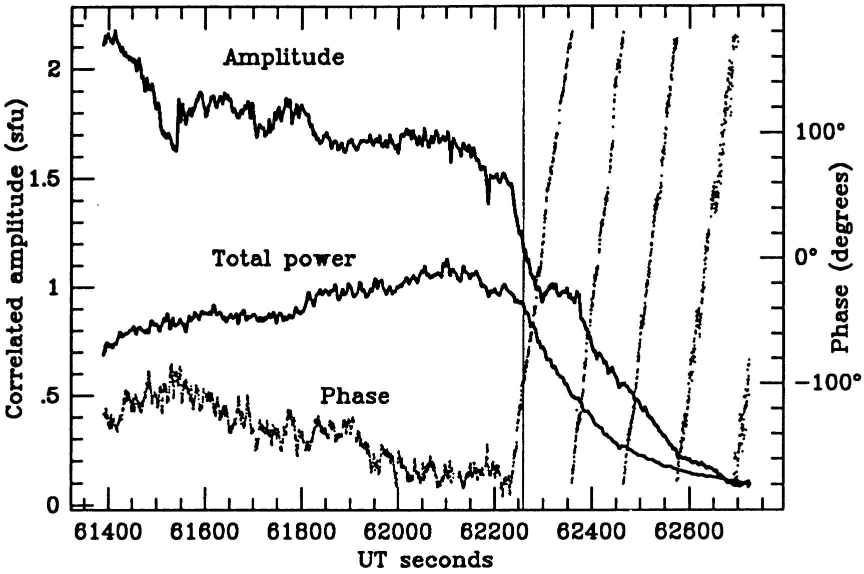

Fig. 1. Data from baseline 12 at BIMA at 89 GHz during first contact. The three curves show the correlated amplitude (solid line), the phase (dots) and the single–dish total power (solid line; arbitrary units). The thin vertical line indicates the time of optical first contact.

no smoothing has been applied to the phase data. The time of optical contact is indicated by a vertical line.

The immediately striking aspect of this figure is the rapid change in the phase properties, which occurs 27 seconds prior to the first contact of the optical limbs. In Figure 2 we show the phase variation at the time of the eclipse on an expanded scale for both sidebands (86 GHz and 89 GHz). Effectively, prior to the arrival of the Moon the phase is a measure of the position of the solar limb where the brightness temperature jumps by 7000 K, and thus the phase is roughly constant with time; variations in the phase prior to the eclipse are primarily due to atmospheric effects. However, once the Moon starts covering the Sun, the effective solar limb begins to move, and the phase begins to change in a linear fashion accordingly (called "phase winding" in radio astronomy). One wind of 360° phase takes about 110 s, corresponding to a distance of 50″, which is consistent with the fringe spacing on baseline 12.

The onset of motion is clearly very sharp. This seems to imply that the Sun's limb at 3 mm wavelength is sharp, although further modelling will be required to determine this. We can estimate the height of the "3-mm limb" from the time between the onset of the eclipse at BIMA, and the ephemeris for the optical eclipse (the latter has been calculated independently by us and by D. Gary, Caltech). From Figure 2, the onset time at BIMA can be determined to better than 1 second; we thus estimate this time difference as 27 ± 1 s, corresponding to a height of 11.9″ ±

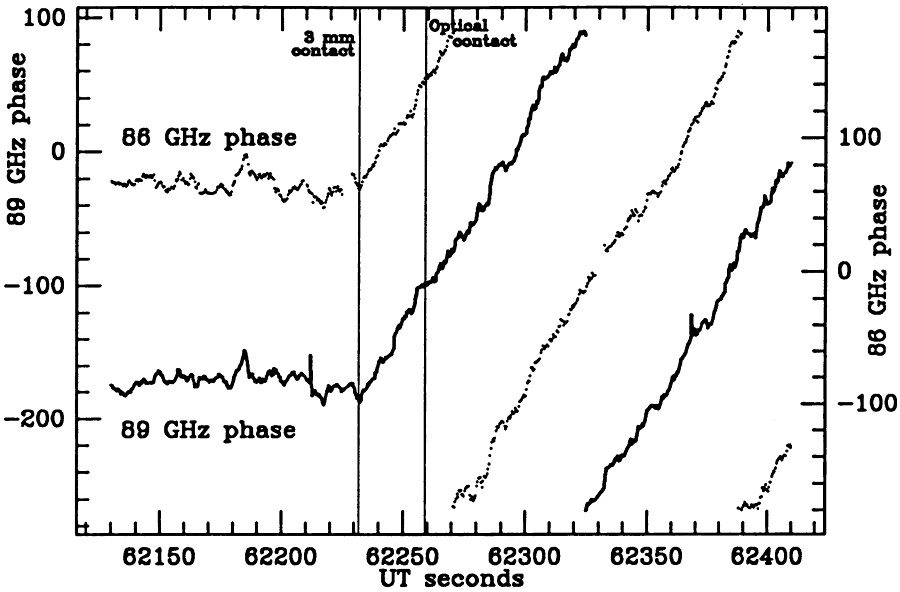

Fig. 2. The variation of the phase with time at both 86 GHz and 89 GHz at the time of first contact. Units are degrees.

0.4″ (8000 km). The onset of the phase winding appears to be very sharp, implying that the contrast at the "3-mm limb" is also sharp. The total power rises somewhat as the eclipse approaches. This is probably due to the warm (220 K) surface of the Moon filling a previously empty region of sky. Note also that the total power curve is typical of previous observations of eclipses at 3 mm: the difference in determining the onset of the eclipse at 3 mm from the phase information and from the total power (or even correlated amplitude) information is readily evident.

4. Chromospheric models

Previous measurements of the height of the limb at similar wavelengths include those of Coates *et al.* (1958; 10″ ± 5″ at 4.3 mm), Takahashi (1967; half-power height of 16″ at 3.0 mm), Simon (1971; < 10″ at 3.5 mm), Swanson (1973; 13″ ± 5″ at 3.2 mm), Labrum *et al.* (1978; 7″ ± 1″ at 3.0 mm), Belkora *et al.* (1992; 7.5″ ± 0.8″ at 3.0 mm) and Horne *et al.* (1981; 8.6″ ± 1″ at 1.2 mm). We note that these measurements are not all directly comparable because most have used comparison of observations with predictions based on models, and different observers have found that different models fit their data best. The observations by Belkora *et al.* (1992) are nearly identical to ours in nature, for the same eclipse, and it is surprising that two such similar experiments should produce such different results. There is always the possibility that a localized large-scale structure at the limb will determine the measured height, but in this case we can see no such structure in the Hα image (there is a filament well south of the field of view). There are no features evident on the limb of the Moon at the relevant location which can explain differences larger than 1″. Thus we do not presently understand the reasons for the difference between our measurement and Belkora *et al.* (1992).

It is well known from previous measurements that the limb height at 3 mm is inconsistent with homogeneous chromospheric models (*e.g.*, those of Vernazza *et al.* 1981 predict a 3-mm height of at most 2000 km or 3″). The explanation most commonly given for this result is that the observed height is actually the top of the forest of spicules which will dominate lines of sight tangent to the solar surface. Spicules are jets of gas seen at the solar limb to be projecting up from the surface through the chromosphere to heights typically of $\sim 8''$. The height measured here at 3 mm wavelength is somewhat larger than in most previous observations. Although spicule heights greater than 10″ are common, they usually occur for individual isolated spicules which would not cover enough of the solar limb to explain a measurement over a large field of view such as this one. Thus it is not clear that the height of 12″ found here for the "3-mm limb" can be explained by the spicule interpretation.

More detailed modelling is required in order to derive a brightness profile across the limb from these data (this has been carried out for the Owens Valley data by Belkora *et al.* 1992). It is however clear from the data that no sharp limb spike, such as those reported by Hagen (1957) and Beckman *et al.* (1975), was observed. We also observed the covering and uncovering of several active regions and a large filament to search for small-scale features, and these data will permit us to obtain some information on the distribution of 3-mm-emitting regions with respect to optical features. Fourth contact was observed in these observations, but no useful data were obtained because none of the baselines were suitably oriented.

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