Modeling the Solar Limb Brightening at 21 cm Wavelength Using Observations with an Interferometer of 3 Small Radio Telescopes

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Abstract

We present modeled images of the Sun from measurements of the interferometric amplitude and closure phase from a 3-baseline interferometer operating at 21 cm wavelength. The data were obtained from 9 June through 7 August 2006. During this period the solar activity was relatively quiet and the data is well fit using a model with equatorial limb brightening which contributes 30±10 percent of the total solar radio flux density. Modeling the image with circularly symmetric Brightening or polar limb brightening does not fit the measurements providing clear evidence that the limb brightening is largely equatorial. During the period of observations, the days with asymmetric images, as indicated by values of the closure phase which deviate from zero to 180 degrees, are well fit by adding from a single sunspot whose best fit position is consistent with the position of the major sunspot in the optical image for that day.

Fig. 1.- View of 3 small radio telescopes tracking the Sun in the parking lot of MIT Haystack Observatory at latitude 42.5˚N 71.5˚W. Observations were taken in "VLBI" mode with 4 MHz bandwidth centered at 1417 MHz. GPS timing was used to synchronize the timing and local oscillators.

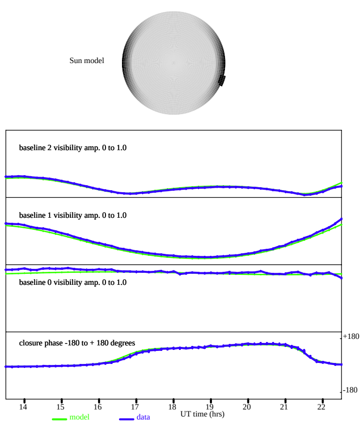

Fig. 2.- Best fit empirical model for 8 July 2006 (day number 189). The r.m.s. residual to the fit is 0.05. The fraction of flux in the limb is 26% of the total Sun's total measured flux density of $40\pm10\times10^{-22}$ W Hz^{-1}m^{-2}. The fraction of flux in the sunspot (NOAA active region AR898) located on the east limb is 7%. The average radio brighteness for this day was approximately 10^5K.

Solar Image Modeling

The Sun's radio image was modeled using weighted least squares to minimize, Q, chi-squared for N observations of closure amplitude and phase on each day where

$$Q=\sum_j\sum_i\left(m_{ij}-a_{ij}\right)^2+\sum_j\left(\cos\left(mc_j\right)-\cos\left(c_j\right)\right)^2+\sum_j\left(\sin\left(mc_j\right)-\sin\left(c_j\right)\right)^2$$

and m_{ij} = model amplitudes
a_{ij} = observed amplitudes
mc_j = model closure
c_j = observed closure phases
i = baseline index, 0 to 2
j = time index, 0 to N-1.

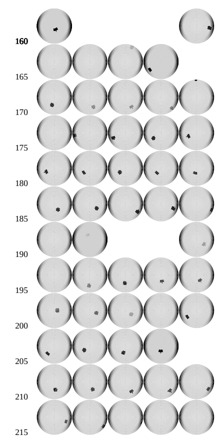

Fig. 3. Sequence of best fit empirical models for days 160 through 219. Sunspot 898 (NOAA AR898) is seen to move across the disk from day 179 through 189.

Results of Image Modeling

From 3 baseline uv coverage we found:

- A uniform disk with equatorial limb brightening with 0.3±0.1 excess fractional flux plus a single sunspot fits the data well.
- Circularly symmetric limb brightening predicted by theoretical model of Smerd (1950) would not fit data

Ray Trace Modeling

In an attempt to explain the lack of limb brightening at the Sun's polar regions and find a model related to the solar environment we used numerical ray tracing with the solar electron density of Selhorts, Silva and Costa (2005) and electron temperatures of Gabriel (1992). The best fit model required the introduction of a latitude dependence to the electron density. We used

$$16\left(1-e^{-h}/10^5\right)e^{-|lat|}+0.6$$

h = height above surface in km
lat = latitude in radians
to approximate solar latitude dependence from the Ulysses spacecraft data (McComas et al (2000)).

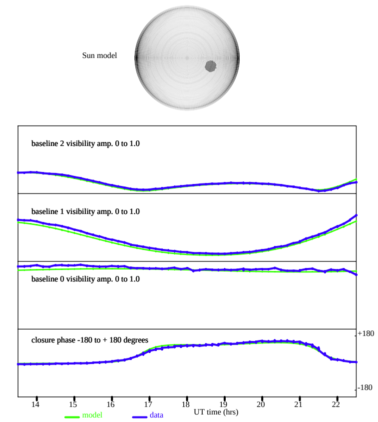

Fig. 4.- Best fit physical model for 8 July 2006. The physical model is based on ray tracing through the solar corona (see text). The r.m.s. residual to the fit is 0.07. The fraction of the flux in the limb is 34%. The fraction of flux in the sunspot is 7%. The fraction of flux in the limb is larger than the best fit empirical model and the sunspot location is displaced. Selhorst Silva and Costa (2005) suggest spicules in the corona as a means of reducing the limb brightening.

Conclusions

Data taken with a 3-element interferometer at 21 cm wavelength with short baselines shows clear evidence for limb brightening in the equatorial regions. Image models based on the corona density and temperature of Gabriel (1992) fit the data better than the older density profiles of the Newkirk (1961) model, but the physical models without spicules or other scattering mechanism produce more limb brightening than the best fit model.

References

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