VLA OBSERVATIONS OF ANGULAR BROADENING CLOSE TO THE SUN

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Abstract. We present synthesis imaging of scatter-broadening of radio sources carried out using the Very Large Array (VLA)* at six radio frequencies during the period of solar minimum. Three compact radio sources were observed from 2 to 16 solar radii around the sun. The data indicate highly anisotropic scattering. The scatter-broadening was estimated from the area of the scattered image and was found to be factor of two lower and orientation of magnetic fields was closer to the radial direction. Present observations confirm the variation of scatter-broadening with solar elongation.

1. Introduction

The density fluctuations in the solar wind plasma scatter radio waves from a distant compact radio source producing rapid variation of its intensity and apparent angular broadening. Ground based studies of these effects have been used to estimate several important properties of the solar wind. In particular, synthesis observations in the last few years show that the solar wind turbulence is highly anisotropic with power law distribution of density fluctuations. The spectral index of the turbulence was found to be closer to the Kolmogorov value of 3.6 over spatial scales of a few tens of kilometers. Scattering is anisotropic which suggests that the turbulence is along well ordered magnetic fields originating from the sun. The direction of magnetic field is roughly orthogonal to the direction of dominant scattering. Anisotropy was found to increase at smaller solar elongations (angular separation between the source and the sun in degrees). Previous measurements during the solar maximum suggested that the angular broadening varies with heliocentric distance as, $(R/R_o)^{-1.6}$ and the direction of solar magnetic field could differ considerably

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TABLE I

Observed range of solar elongations and wavebands

Band			K	U	X	C	L	P
Elongation		λ	0.13 cm	2 cm	3.5 cm	6 cm	20 cm	90 cm
(deg)	$(R/R_\odot)$							
0.53°	2.1		R	R	R			
0.89°	3.6				F	F		
1.47°	5.9				F	NF		
2.42°	9.7					NF	NF	
3.51°	14.0					F	F	U
4.21°	16.8						NF	U
Beam	(asec)		0.07	0.14	0.3	0.4	1.4	7.2

R – resolved, U – unresolved, F – fitted with 2-D gaussian, NF – fit was not possible.

from the expected radial direction (Armstrong *et al.*, 1986; Armstrong *et al.*, 1990; Narayan *et al.*, 1989; Anantharamaiah *et al.*, 1994).

2. Observations

The observations were made in July 1995 during the solar minimum. Three compact radio sources 0839+187, 0829+187 and 0851+202 were selected from the VLA list of calibrators. Observations were made on two consecutive days at six VLA frequencies. The lines of sight to the sources spanned about 2–17 $R_\odot$. Since the density of the solar wind decreases as $(R/R_o)^{-2}$ and the scattering increases as λ^2, for a given combination of frequency and range of interferometric baselines, optimal angular broadening occurs only within a narrow range of elongations. Scattering parameters can be estimated reliably at these elongations. We selected the observing frequencies to match the estimated angular broadening at each elongation. Lower scattering strengths were expected during the solar minimum (Manoharan *et al.*, 1994; Anantharamaiah, 1994; Yamaguchi *et al.*, 1995). Table I gives the log of observations and wavebands used for a total of 14 epochs.

The analysis presented here was made in the image domain. For each epoch, the angular-broadened source was imaged after self-calibrating the data. Figure 1 shows an example of a scatter-broadened image. At the minimum elongation of 0.53°, the sources were highly resolved and thus could not be imaged. At the largest elongation of 4.21°, the sources appeared as un-scattered point sources. For five epochs, the data in the image plane were fitted with a two-dimensional gaussian to obtain the major axis (θ_{maj}), minor axis (θ_{min}), anisotropy (ρ) and position angle (P.A.). Table II gives the list of best-fit parameters obtained. For rest of the epochs

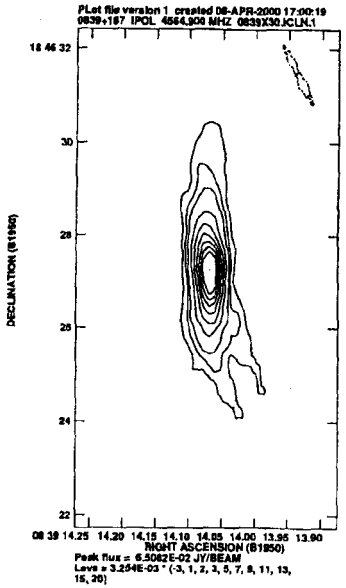

Figure 1. Scatter-broadened image of 0839+187 observed at $\lambda = 6$ cm at a solar elongation of 0.89°.

TABLE II

Parameters of angular broadened image

Source	Band	Elongation (deg)	θ_{maj} (asec)	θ_{min} (asec)	ρ	P.A. (deg)
0839+187	X	0.89	1.4	0.5	2.8	19
0839+187	C	0.89	8.1	2.0	4.0	4
0829+187	C	1.47	1.40	0.95	1.5	−16
0829+187	C	2.42	0.9	0.8	1.1	17
0829+187	L	2.42	5.5	3.0	1.8	−18

the sources were marginally scattered and estimate of their angular broadening could not be made.

3. Discussion

The strength of scattering, estimated from the area of the scatter-broadened images, was found to be a factor of two lower than that measured during the solar maximum by Anantharamaiah *et al.* (1994) at the corresponding elongations. Solar wind re-

mained highly anisotropic, as can be seen from high axial ratios for the images. The direction of the magnetic field was estimated from the position angle of each image. The orientation of the solar magnetic field was found to be close to the expected radial direction during the period of solar minimum.

References

Anantharamaiah, K.R., Gothoskar, P. and Cornwell, T.J.: 1994, Radio synthesis observations of scattering in the inner heliosphere, *Astron. Astrophys.* **15**, 387.

Armstrong, J.W., Coles, W.A., Rickett, B.J. and Kojima, K.: 1986, Solar wind observations near the sun, *The sun and the Heliosphere in three dimensions, Proc. of the 19th ESLAB Symposium*, Les Diablerets, 59–64.

Armstrong, J.W., Coles, W.A., Kojima, M. and Rickett, B.J.: 1990, Observations of field-aligned density fluctuations in the inner solar wind, *Astrophys. J.* **358**, 685–692.

Narayan, R., Anantharamaiah, K.R. and Cornwell, T.J.: 1989, Refractive radio scintillation in the solar wind, *Mon. Not. R. Astron. Soc.* **241**, 403–413.

Manoharan, P.K., Kojima, M. and Misawa, H.: 1994, The spectrum of electron density fluctuations in the solar wind and its variations with solar wind speed, *Geophys. Res.* **99**, 23411–23420.

Yamauchi, Y., Misawa, H., Kojima, M., Mori, H., Tanaka, T., Takaba, H., Kondo, T., Tokumaru, M. and Manoharan, P.K.: 1995, Observations of micro-turbulence in the solar wind near the sun with interplanetary scintillation, *Solar Wind-8, Conf. Proc.*, 82.