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INTERSTELLAR SCATTERING OF COMPACT RADIO SOURCES NEAR SUPERNOVA REMNANTS

STEVEN R. SPANGLER,[1] ROBERT L. MUTEL,[1] JOHN M. BENSON,[2] AND JAMES M. CORDES[3]
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ABSTRACT

We report a multifrequency, VLBI search for interstellar scattering of extragalactic radio sources near supernova remnants. VLBI observations at 610, 1663, and 4991 MHz were made of compact sources near the supernova remnants CTA 1, G33.6+0.1, G74.9+1.2, and HB 21, and 610 MHz observations made of a source near HB 9. These observations were motivated by the possibility of enhanced cosmic-ray–induced turbulence in front of supernova remnants, as expected in "diffusive" theories of shock wave acceleration. Angular broadening is definitely seen in the case of the source 2013+370, which lies within 4′ of the supernova remnant G74.9+1.2. Our present observations cannot unambiguously attribute the scattering material to the supernova remnant, as the line of sight also passes through the Cygnus OB1 association. The source 1849+005 appears to be highly scattered, as we did not detect fringes, even on short baselines at 5 GHz. This result may be due to the low galactic longitude of this source rather than its proximity to the supernova remnant G33.6+0.1. Broadening was not detected for sources whose lines of sight pass close to the supernova remnants HB 9, HB 21, and CTA 1.

Subject headings: interferometry — nebulae: supernova remnants — turbulence

I. INTRODUCTION

Since the discovery of pulsars, it has been realized that plasma turbulence in the interstellar medium produces detectable scattering of radio waves. A thorough discussion of the theory and observations of this phenomenon in given by Rickett (1977). The recent study of pulsar scattering by Cordes, Weisberg, and Boriakoff (1985) indicates that the scattering medium is composed of two components. The first is a tenuous, distributed component, while the second consists of highly clumped regions of intense turbulence.

Identification of the type of astronomical object associated with these turbulent clumps is of importance, both to studies of the interstellar medium and plasma astrophysics generally. Cordes, Weisberg, and Boriakoff (1985) state that the scale height of the turbulent clumps is characteristic of Population I objects. Obvious possibilities then include H II regions, stellar winds from massive stars, and supernova remnants.

We are carrying out a program to determine the nature of this clumped, turbulent material. The observational technique is to look for enhanced angular broadening of extragalactic radio sources whose lines of sight pass through or close to objects of interest. Dennison *et al.* (1984) have previously made such observations, for similar purposes. Extragalactic sources are generally inferior to pulsars in scattering studies, in that fewer techniques are applicable, and the intrinsic source structure must be considered in angular broadening measurements. However, the main scattering phenomenon which can be observed for extragalactic sources, angular broadening, is also the easiest to interpret in terms of the scattering medium, and is observable with standard VLBI interferometers. Furthermore, the high surface density of extragalactic sources increases the chances of an object being along a line of sight of interest. Finally, since scattering angular diameters scale as roughly the square of the observing wavelength, multifrequency VLBI observations can distinguish intrinsic structure from angular broadening.

In this paper, we report and discuss multifrequency VLBI observations of extragalactic radio sources whose lines of sight pass close to, but *outside*, the radio continuum shells of supernova remnants. There are two reasons that such observations are of interest to the matters discussed above. First, one would like to empirically investigate the possibility that enhanced turbulence exists outside the radio continuum shell of a supernova remnant. Dennison *et al.* (1984) noted a number of sources with enhanced broadening whose lines of sight pass *close* to supernova remnants. Furthermore, it may be difficult for supernova remnants to account for all of the clumped component discussed by Cordes, Weisberg, and Boriakoff 1985), if only the region interior to the radio continuum shell is responsible for enhanced scattering.

The second, and main, motivation for these observations results from theoretical considerations. In recent years, considerable theoretical effort has been investigated in "diffusive" theories of cosmic-ray acceleration by shock waves (Axford, Leer, and Skadron 1977; Bell 1978; Blandford and Ostriker 1978). An attraction of these theories is that they are a variation on the venerable Fermi mechanism. The shock waves provide the "moving wall," and self-generated Alfvén waves provide a "stationary wall." The Alfvén waves are generated by particles, either produced at or reflected by the shock wave, which flow into the upstream region. Streaming particle distributions are unstable to the growth of Alfvén waves. The Alfvén waves, in turn, scatter the particles in pitch angle, producing an isotropic particle distribution. The particles are therefore confined to a thin layer upstream of the shock, repeatedly overtaken, and accelerated.

A powerful argument in favor of the diffusive mechanism is its apparent operation in the solar wind, most notably at Earth's bow shock (Lee 1982). In the region upstream of the bow shock, all the constituents of the diffusive theory are seen,

[1] Department of Physics and Astronomy, The University of Iowa.
[2] National Radio Astronomy Observatory.
[3] Astronomy Department, Cornell University.

such as ion beams streaming into the solar wind, large-amplitude Alfvén waves generated by these beams, and isotropic, energized ions which have been scattered by the Alfvén waves and accelerated by repeated shock crossings. Measurements of these phenomena are in semiquantitative as well as qualitative agreement with the diffusive theories.

We now consider whether we can demonstrate operation of the diffusive mechanism in supernova remnants, the alleged source of the galactic cosmic rays. A distinctive feature of diffusive acceleration theories is the upstream wave scattering layer. The waves in this layer hold the particles close to the shock wave via pitch-angle scattering, where they can be repeatedly overtaken and accelerated. One could contend that given the existence of this upstream wave layer and the phenomenon of pitch-angle scattering, diffusive acceleration is virtually inevitable. Detection of a layer of intense Alfvén waves upstream of a supernova shock would furnish compelling support for the diffusive cosmic-ray acceleration theories.

These Alfvén waves should produce, via a number of nonlinear processes such as modulational instabilities, corresponding plasma density fluctuations. Spacecraft observations in Earth's foreshock region support this contention (Fredricks *et al.* 1972) in the case of solar wind Alfvén waves. These density fluctuations might then reveal themselves by producing angular broadening of compact radio sources behind the turbulent layer. A goal of this experiment is, therefore, to search for such Alfvén wave induced density fluctuations upstream of supernova shocks. We are limited in this endeavor by the unknown thickness of the upstream wavelayer, and by the small number of suitable extragalactic radio sources in the vicinity of supernova remnants.

II. OBSERVATIONS

We have searched the supernova remnant literature for radio sources which satisfy the following three criteria: (1) they are compact ($\theta \ll 1''$), as determined by their spectra or previous VLBI observations; (2) they are in close proximity ($< 1°$) to a supernova remnant, so their line of sight plausibly passes through the upstream wave layer of the SNR; and (3) they have sufficient flux density to observe with the Mark II VLBI system. A list of five sources so chosen is given in Table 1.

Column (1) gives the source name, and column (2) lists the galactic longitude and latitude of the source. Columns (3) and (4) give, respectively, the supernova remnant associated with the source and the assumed remnant distance. Column (5) lists the "impact parameter," or minimum separation of the radio source line of sight and the radio continuum shell, which we identify with the SNR shock. Column (6) lists the scattering angular diameter (at 1 GHz), or upper limit, and column (7) gives an additional measure of the strength of scattering. Both of these quantities are described below. Finally, column (8) lists the reference for the supernova remnant distance. In Figure 1 we reproduce from the literature maps showing the five supernova remnants and the nearby radio sources which were the objects of our VLBI observations.

Observations of the sources in Table 1 were made with Mark II VLBI interferometers at frequencies of 610, 1663, and 4991 MHz. Observations at three frequencies were made in order to separate intrinsic structure from angular broadening, which is roughly proportional to the square of the wavelength.

The 610 MHz observations were made in 1984 August, utilizing a three-element interferometer consisting of the Owens Valley Radio Observatory (OVRO) 41 m, the NRAO[4] 43 m, and the North Liberty Radio Observatory (NLRO) 18 m antennas. Observations at 4991 MHz were made in 1984 October utilizing the 100 m antenna of the Max-Planck-Institut für Radio Astronomie (MPI), the 37 m Haystack antenna, NRAO, and OVRO. The 1663 MHz observations were made in 1984 December with a five-element interferometer consisting of MPI, NRAO, NLRO, OVRO, and the phased VLA. For each source and frequency, observations consisted of one-half hour scans at a few hour angles, rather than "full synthesis" observations. The structural information reported in this paper is therefore rather rudimentary.

We now comment briefly on our observations of each of the sources listed in Table 1.

a) 0016+731

The line of sight to this source passes about 30′ beyond the radio continuum shell of CTA 1. Theoretical arguments based on diffusive acceleration theories (Axford 1981) indicate that the bulk of the cosmic rays result from supernova remnants with the size and expansion speed of CTA 1 (Sieber, Salter, and Mayer 1981). At 5 GHz 0016+731 is highly compact. A fit of a Gaussian model for the brightness distribution yields an angular diameter of ~ 0.7 mas, in satisfactory agreement with the observations of Eckart *et al.* (1982). Nonzero closure phases indicate the existence of discernible structure. Pearson and Readhead (1984), on the basis of observations made in 1982, describe 0016+731 as "very compact" at 5 GHz, i.e., with visibility $> 95\%$ on transatlantic baselines. Our limited observations indicate more resolution and suggest structural variations during the period 1982–1984. At 1663 MHz, the source can be approximately modeled with a highly elliptical Gaussian of major axis 3.3 mas, axial ratio 0.25, and position angle of 130°. Our limited 610 MHz data are adequately modeled by an elliptical Gaussian model of similar axial ratio

[4] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract from the National Science Foundation.

TABLE 1

VLBI SOURCES NEAR SUPERNOVA REMNANTS

Source (1)	l, b (2)	Associated SNR (3)	Assumed Distance (kpc) (4)	Impact Parameter (pc) (5)	θ_1 GHz (mas) (6)	$C_N^2 Z$ ($m^{-20/3}$ pc) (7)	Reference (8)
0016+731	120°6, 10°7	CTA 1	1.1–1.9	8.5–14.5	≤8	≤8.4	Sieber *et al.* 1981
0503+467	161°0, 3°7	HB 9	1.1	≤1.6	≤4	≤2.6	Willis 1973
1849+005	33°3, 0°2	G33.6+0.1	7–10	16–23	≥350	≥4600	Caswell *et al.* 1981
2013+370	74°9, 1°2	G74.9+1.2	12	13	42	134	Weiler 1983
3C 418	88°8, 6°0	HB 21	1	3.5	<8	<8.4	Hill 1974

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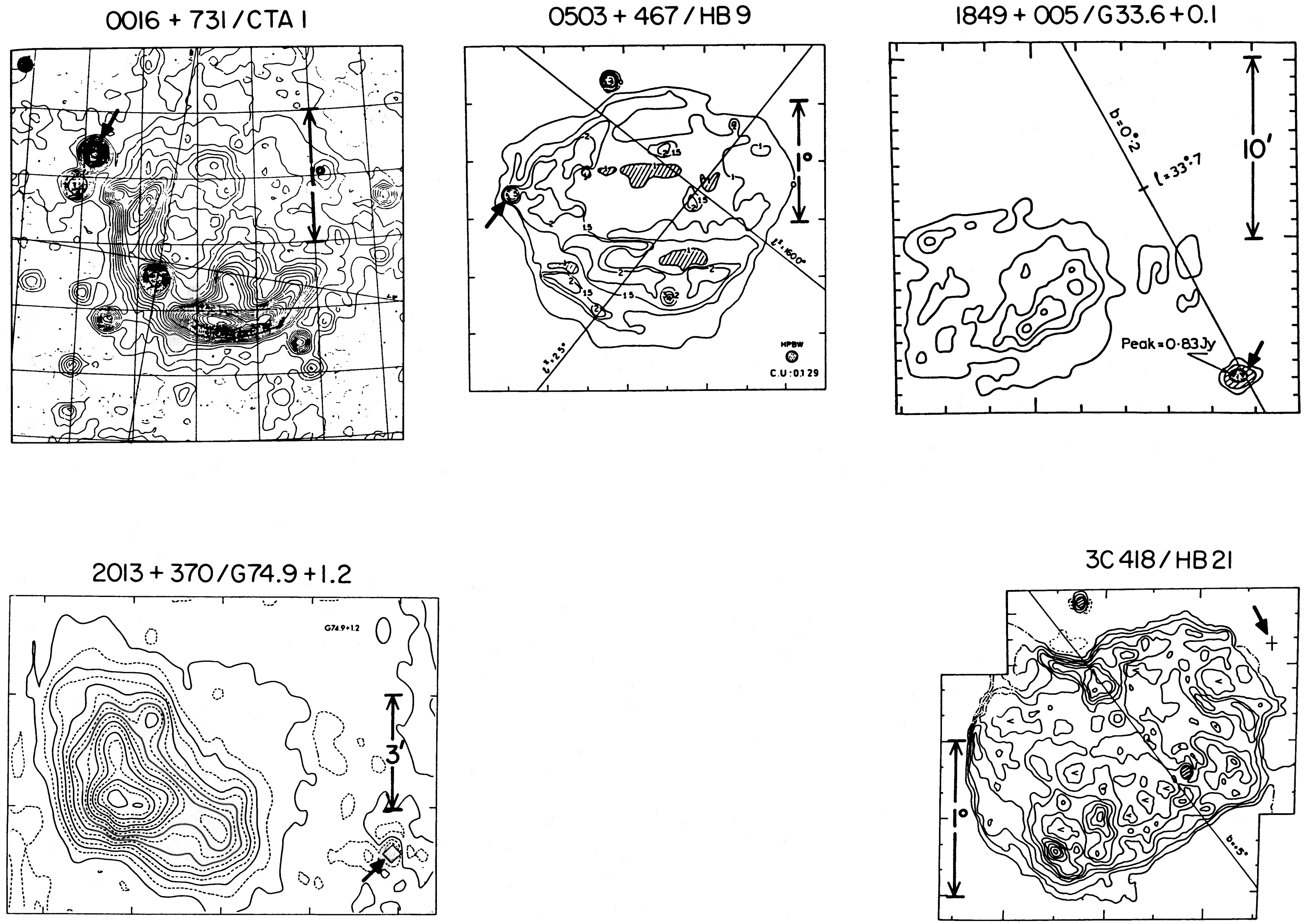

FIG. 1.—Published maps of supernova remnants, showing nearby compact radio sources which were observed with VLBI interferometers. Arrows point to sources which were observed, and the angular scale of the maps are indicated. These pictures show how close the line of sight to the radio source passes to the SNR, as well as the orientation of the line of sight with respect to major features of the SNR. References for the maps are as follows: CTA 1, Sieber, Salter, and Mayer (1981); HB 9, Willis (1973); G33.6 + 0.1, Caswell, Milne, and Wellington (1981); G74.9 + 1.2, Duin *et al.* (1975); HB 21, Hill (1974).

and position angle as that described above, and a major axis of 20 mas. This source therefore shows a pronounced increase of angular size with wavelength, as would be expected for turbulent broadening. However, 1663 MHz closure phases on the MPI-OVRO-NRAO triangle depart from zero by as much as 30°, an indication of complex structure unrelated to scattering. While further observations of this source are warranted, for the present we consider the 3 mas at 1663 MHz as an upper limit to the scattering angular diameter. Assuming a λ^2 dependence of the scattering size, this would correspond to 8 mas at 1 GHz, which is listed in column (6) of Table 1.

b) 0503+467

This source lies extremely close to the edge of the supernova remnant HB 9. An examination of the radio map of Reich, Fürst, and Sieber (1983) shows that the source is barely distinguishable from the SNR radio continuum emission. This source is therefore of interest in that it may provide quite deep penetration of the upstream wave layer.

The source was observed four times during a 5 hr period at 610 MHz, the only frequency for which observations were made. The observations were fitted with a circular Gaussian model of angular diameter (FWHM) 10 mas. We adopt this angular size as an upper limit to the angular broadening. Assumption of a λ^2 dependence of the scattering size yields 4 mas at 1 GHz.

It is interesting to note that Pynzar and Udaltsov (1983) report HB 9 as being one of four supernova remnants for which a scintillating component was detected at 102 MHz. Presumably the object detected was 0503+467. Pynzar and Udaltsov report that the angular size at 102 MHz is less than 0″.1, which would provide an upper limit to the 1 GHz scattering angle of 1 mas.

c) 1849+005

The line of sight to this object passes about 8′ from the edge of the supernova remnant G33.6+0.1. Its extragalactic nature is indicated by its flat spectrum (Caswell, Milne, and Wellington 1981; Seaquist and Gilmore 1982), compactness at arcsecond resolution (Seaquist and Gilmore 1982), and reported variability (Ryle *et al.* 1978). In spite of these auspicious properties, we failed to detect fringes in any experiment. If this is due to angular broadening, then the implied angular size at 5 GHz is in excess of 14 mas (visibility <0.15 on a projected baseline of $10^7\lambda$ [NRAO-Haystack]). This corresponds to a 1 GHz broadening size in excess of 350 mas. Dennison *et al.* (1984) also failed to detect fringes in a 408 MHz VLBI experiment. Their results are consistent with those presented here.

d) 2013+370

The line of sight to this source passes about 3′.5 from the SNR G74.9+1.2, classified by Weiler (1983) as a "plerion" or Crab Nebula–like supernova remnant. Shaffer *et al.* (1978) initially suggested that the source was affected by angular broadening. Geldzahler, Shaffer, and Kühr (1984) have recently published a 10.6 GHz VLBI map of this source, which shows two compact components separated by about 2.5 mas.

Our observations show the source to be heavily scattered at frequencies below 5 GHz. In Figure 2, we present measurements of correlated flux density versus projected baseline length at 4991 and 1663 MHz. The solid lines correspond to circular Gaussian models with angular diameters of 2 and 15 mas at 4991 and 1663 MHz, respectively. The scatter of the data about these curves appears to be primarily due to departures of the source structure from circular symmetry, as discussed below. At 610 MHz, the source was only detected during a single scan on the NLRO-NRAO baseline, at which time the projected baseline length had decreased to its minimum value of 8×10^5 wavelengths. The fringe visibility at this time was 0.40 ± 0.10. These observations indicate that despite a significant decrease in baseline length (normalized by the wavelength) at lower frequencies, the source is also more heavily resolved. This indicates a strong dependence of angular size on wavelength, as expected for interstellar scattering.

Estimates of the angular size at the two higher frequencies of observation were made by model fitting. At 5 GHz, the source was modeled by two components having the separation and position angle reported by Geldzahler, Shaffer, and Kühr (1984). A search was then made for the best fitting component flux ratio and (the parameter of interest to us) angular size, taken to be the same for each component. This analysis indicated that the component angular size, possibly representing a combination of intrinsic and scattered structure, is 1.5–2 mas.

At 1663 MHz, the source appears to be better fitted by an elliptical than a circular Gaussian model. The best fit model yields a major axis of 19 mas, an axial ratio of 0.6, and a position angle near 0°. A confident detection of asymmetric broadening would be very important, as it would indicate either the presence of anisotropic scattering irregularities, or asymmetric focusing by large-scale (refracting) irregularities. Higdon (1984) has argued for anisotropic density irregularities in the interstellar medium. However, in view of our limited data set, we consider the present evidence to be highly tentative. We adopt, as our measurement of broadening at this frequency, the geometric mean of the major and minor axes, which is 15 mas.

At 610 MHz, our single fringe detection implies a Gaussian angular diameter of 130 ± 40 mas. A plot of our angular size measurements versus observing wavelength is shown in Figure 3. The solid line represents a dependence of angular size on the square of the observing wavelength.

The results of Figures 2 and 3 present a very strong case for interstellar scattering of 2013+370. First, the measured angular sizes at 1663 and 610 MHz are considerably larger than those observed for high-latitude sources with similar spectra and variability characteristics. Second, as shown in Figure 2, the measured angular sizes are in conformity with the expected λ^2 dependence. The interpolated broadening size at 1 GHz is 42 mas.

e) 3C 418

The line of sight to 3C 418 passes within 12′ of the supernova remnant HB 21. Previous lower resolution observations of this source reveal a curious "bent jet" structure at scales of roughly 0″.1–1″ (Muxlow, Jullian, and Linfield 1984). Our VLBI observations indicate complicated structure at the milliarcsecond level. To obtain estimates of angular broadening (or limits thereto), hybrid maps were made of the source at 1663 and 4991 MHz. A bright "central component" was identified on these maps, which was used for broadening estimates. Estimates for the angular size of this component, which may be considered an upper limit to the broadening angular size, are 1 mas at 5 GHz and 3 mas at 1.66 GHz.

The 610 MHz observations are of limited utility due to their paucity and the complex nature of the source. Strong fringes were observed, with detectable closure phase excursions from

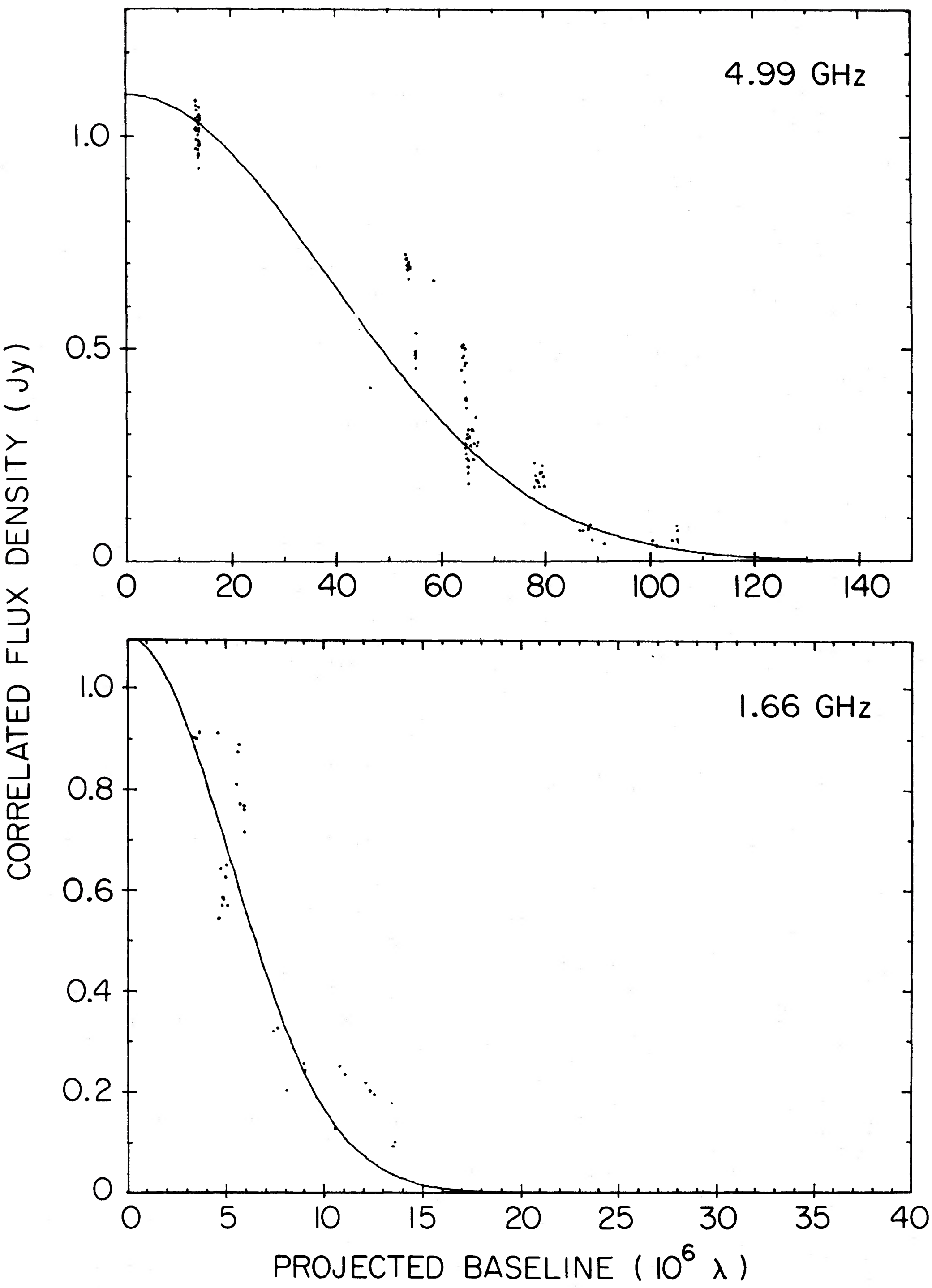

FIG. 2.—Observations of 2013+370 at 4991 and 1663 MHz. Plotted are the correlated flux density vs. projected baseline length (in millions of wavelengths. Solid curves represent Gaussian models with diameters (FWHM) of 2 and 15 mas.

zero. These observations suggest that broadening is not dominant at 610 MHz.

We have used our 1.66 GHz observations to set an upper limit of 8 mas to the 1 GHz broadening size.

III. DISCUSSION

Of the five sources we have observed, two (0503+467 and 3C 418) show no indication of broadening, in spite of the fact that they possess the smallest impact parameters in our sample. Firm upper limits to the scattering angular size of 4–8 mass at 1 GHz are reported.

For the source 0016+731, which is in proximity to the SNR CTA 1, we cannot exclude the possibility of broadening at low frequencies (610 MHz). At the present, intrinsic source structure appears to be a more likely explanation for our observations. We estimate the scattering size at 1 GHz to be less than, or equal to, 8 mas.

In the remaining two cases, 1849+005, associated with

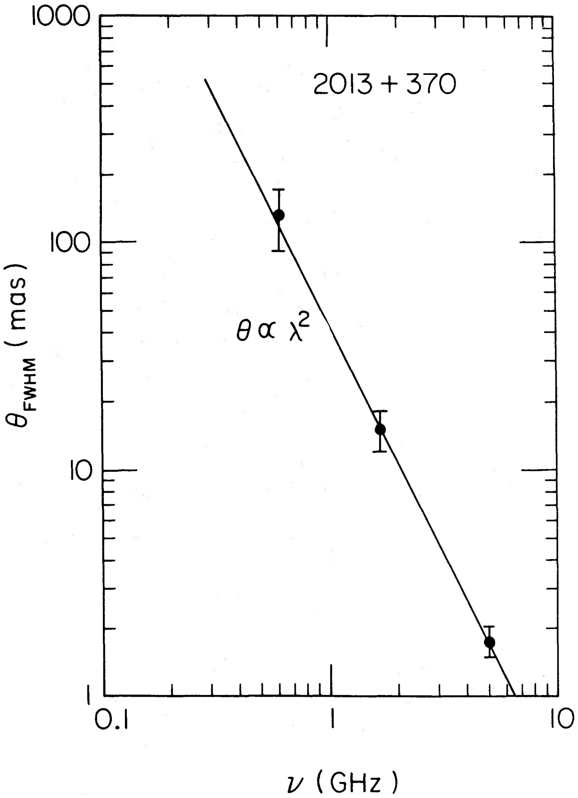

FIG. 3.—Measured angular size of 2013+370 as a function of frequency. The data show the angular size scaling as the square of the wavelength, as expected for scattering.

G33.6+0.1, and 2013+370, associated with G74.9+1.2, we believe we have observed interstellar scattering. For 1849+005, this contention is tentatively based on the nondetection of VLBI fringes. A measurement of angular size using shorter (~100 km) baselines is necessary to confirm the scattering hypothesis.

If is of interest to compare our observations with the level of scattering predicted from pulsar observations. Pulsar scintillations are parameterized in terms of the quantity C_N^2, which is the normalization constant of the electron density power spectrum (Rickett 1977; Cordes, Weisberg, and Boriakoff 1985)

$$P(q) = C_N^2 q^{-\alpha} , \qquad q_0 < q < q_1 , \tag{1}$$

where q is the spatial wavenumber, and α is the spectral index. The quantities q_0 and q_1 represent wavenumbers corresponding to, respectively, the "outer scale" and "inner scale" of the turbulence, and we shall adopt a value of $\alpha = 11/3$ (Armstrong, Cordes, and Rickett 1981). From formula (A5) of Cordes, Weisberg, and Boriakoff (1985), we obtain the following relation between C_N^2 and the scattering angular diameter at 1 GHz:

$$\theta_{\rm FWHM} = 2.24(C_N^2 Z_{\rm pc})^{0.6} \text{ mas} . \tag{2}$$

where $Z_{\rm pc}$ is the path length in parsecs, and C_N^2 is in the customary units of $m^{-20/3}$. Equation (2) has been used to calculate the product $C_N^2 Z_{\rm pc}$ for each of our sources, and the results are given in Table 1, column (7). The highest such value is obtained for 1849+005. Pulsar observations (Cordes, Weisberg, and Boriakoff 1985) reveal heavy scattering in the direction of 1849+005. Pulsars in the vicinity of this source, such as 1845−01, 1859+03, and 1900+01, have values for $C_N^2 Z_{\rm pc}$ of 252–540; large, but smaller than the lower limit inferred for 1849+005. In view of the greater distance traversed by the 1849+005 radiation, it seems plausible that the observed scattering is due to "incidental" turbulence unrelated to the supernova remnant.

The scattered nature of 2013+370 is far more secure, being based on measurements at three frequencies and on a range of baselines. The location of the turbulent material responsible for this broadening is not obvious. This source was observed because of its angular proximity to the SNR G74.9+1.2. However, 2013+370 also lies behind the "Cygnus superbubble" (Bochkarev and Sitnik 1985), a part of the sky characterized by numerous H II and stellar wind regions. In fact, the line of sight to 2013+370 passes through the Cygnus OB1 association. It is therefore quite plausible that the scattering material responsible for the broadening of 2013+370 lies in the Cygnus superbubble rather than in the vicinity of the supernova remnant G74.9+1.2.

It should be pointed out, however, that 3C 418 also lies behind the Cygnus superbubble, in proximity to the Cygnus OB7 association (Bochkarev and Sitnik 1985). Our observations show it to be considerably less scattered than 2013+370, so a line of sight through the Cygnus region does not ensure enhanced broadening.

We now consider the implications of our observations for theories of diffusive shock acceleration. Specifically, we would like to know if these observations can place constraints on the properties of plasma upstream of a supernova remnant shock. In an interpretation of our observations, two questions must be considered. First, is it likely that the upstream wave layers will extend as far as the impact parameters listed in Table 1? Second, even if the layers are so extensive, will the turbulence in the upstream layers be sufficiently intense to produce observable scattering?

Unfortunately, the answers to both questions rely on unknown or poorly known attributes of the supernova shock and the interstellar medium. In what follows, we will present crude considerations, deferring a complete discussion to a later paper.

The extent of the upstream layer is determined by a balance between convection of the particles (back onto the shock) and diffusion due to magnetic irregularities (Blandford and Ostriker 1978). The extent of the region is $l \approx D_Z/V$, where D_Z is the spatial diffusion coefficient, and V is the shock speed. A rough estimate of the spatial diffusion coefficient is $D_Z \approx v^2/D_\mu$, where v is the particle speed and D_μ is the pitch angle diffusion coefficient. Using well known expressions for D_μ (i.e., Wentzel 1974), we obtain the following estimate for the extent of the wave layer,

$$l \approx \frac{v^2}{V} \frac{\gamma}{\Omega_0} \left(\frac{B_0}{b}\right)^2 \eta , \tag{3}$$

where γ is the Lorentz factor of the particles responsible for generation of the wave layer, Ω_0 is the (nonrelativistic) cyclotron frequency, B_0 and b are, respectively, the static and wave magnetic field strength, and η is the fractional bandwidth of the excited waves.

Assuming that ions are the principal species accelerated (as is the case for Earth's bow shock and traveling interplanetary shocks), equation (3) becomes:

$$l \approx 3 \times 10^{-3} \frac{\gamma}{V_{100} B_{-6}} \left(\frac{B_0}{b}\right)^2 \eta \text{ pc} , \tag{4}$$

where V_{100} is the shock speed in units of 100 km s^{-1}, and B_{-6} is the magnetic field strength in units of 10^{-6} G.

Equation (4) reveals our great uncertainty regarding the extent of the upstream region. For a plausible choice of $V_{100} = 5$, $B_{-6} = 1$, $\gamma = 100$, $b = 0.10\ B_0$, and $\eta = 1$, we have $l \approx 5$ pc, comparable to the impact parameters listed in Table 1. Equally plausible choices can result in wave-layer estimates far greater or far smaller. About all we can say at the present time is that the impact parameters probed in our experiment are not absurdly larger than the plausible size of upstream regions.

It is relevant to note that Morfill, Drury, and Aschenbach (1984) have recently interpreted reported X-ray halos about supernova remnants in terms of microphysical processes in wave-scattering layers. If the interpretation of Morfill *et al.* is correct, the upstream-scattering layers are very large, of order one-third of the remnant radius, and the lines of sight studied in this project would pass through the SNR foreshocks.

We now estimate the broadening expected from passage through a supernova foreshock. Equation (2) may be rewritten in terms of the turbulence properties as,

$$\theta_{\rm FWHM} = \frac{8.0 \times 10^7\, \sigma_n^{\,1.2} Z_{\rm pc}^{\,0.6}}{L_0^{\,0.4}}\ {\rm mas}\ . \qquad (5)$$

In equation (5), σ_n is the rms electron density fluctuation (cm^{-3}), L_0 is the outer scale of the turbulence (cm), and $Z_{\rm pc}$ is the thickness of the scattering layer (in parsecs).

A number of assumptions are contained in equation (5). We assume plane waves incident on the scattering medium, which should be a valid assumption for extragalactic radio sources viewed through the interstellar medium. We assume the inner scale of the turbulence is zero, i.e., undetectably small. Finally, we have adopted a Kolmogoroff turbulence spectrum, meaning that α in equation (1) is set equal to 11/3. Armstrong, Cordes, and Rickett (1981) present evidence that a Kolmogoroff spectrum characterizes the interstellar medium generally. It remains to be determined whether supernova foreshock turbulence also has this characteristic. For the present, we note that the Kolmogoroff model has two free parameters determining the intensity (σ_n) and scale (L_0) of the turbulence. Further refinements are not warranted by the present observations. Equation (5) is presented graphically in Figure 4. Here the scattering angle is plotted against the outer scale size for $\sigma_n = 0.01$ and 0.1 cm^{-3}. Reasons for consideration of this range for the rms density fluctuation are given below. We have chosen $Z_{\rm pc} = 10$, which should be roughly appropriate for the supernova remnants studied here. The horizontal dashed lines represent our angular size measurements or limits.

For the foreshock regions of CTA 1, HB 9, and HB 21, sampled by the sources 0016+731, 0503+467, and 3C 418, we infer that the outer scale must be larger than 10^{13} cm if $\sigma_n = 0.01$, and larger than 10^{16} cm if $\sigma_n = 0.1$. For 2013+370, the observed scattering could result if the rms density fluctuation was 0.1 cm^{-3}, and the outer scale to the turbulence was $\sim 10^{14}$ cm.

The limits for 0016+731, 0503+467, and 3C 418 are sufficient to provide some interesting constraints on the outer scale of the turbulence, particularly if larger values for σ_n are appropriate. There appears to be evidence that matter upstream of supernova remnants is characterized by densities ≥ 1 cm^{-3} (DeNoyer 1975; Falle and Garlick 1983; Petre *et al.* 1983), i.e., significantly greater than the general interstellar medium. Blandford (1982) briefly comments on this matter and suggests

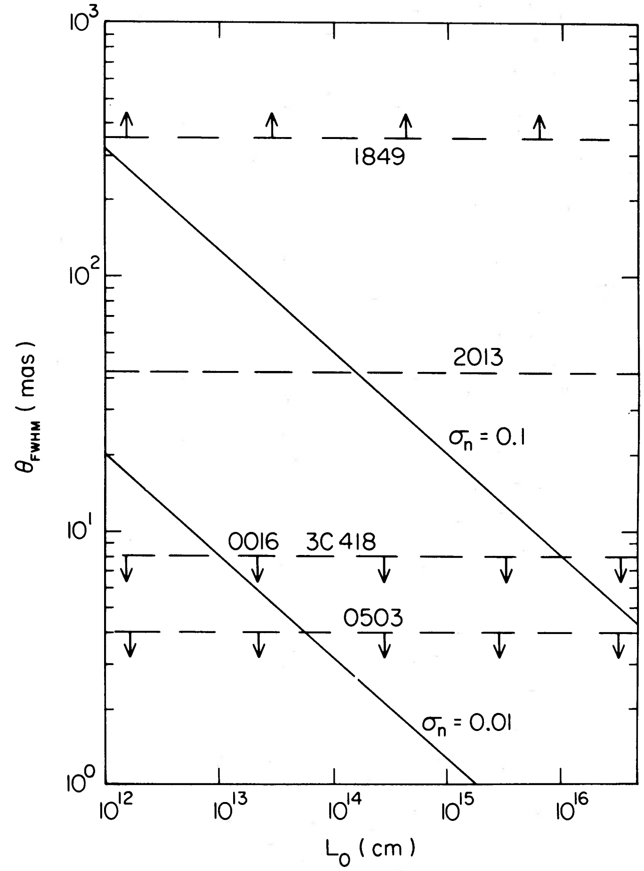

FIG. 4.—Expected scattering in an SNR upstream wave layer. We plot scattering angular size as a function of outer scale size for rms density fluctuation equal to 0.01 and 0.1 cm^{-3}. Horizontal dashed lines represent our measurements of the sources near supernova remnants.

that radio supernova remnants result from supernovae which happen to occur in denser parts of the interstellar medium. Alfvén wave-induced density fluctuations in Earth's foreshock can be 20%–40% of the ambient density (see Fig. 2 of Fredricks *et al.* 1972). We can therefore contend that the rms electron density fluctuation upstream of a supernova remnant is probably considerably in excess of 0.01 cm^{-2}, and might be larger than 0.1 cm^{-3}.

If we adopt an rms of 0.1 cm^{-3}, we would conclude that the outer turbulence scale is at least 10^3 astronomical units. Assuming that one equates the size of irregularities with the gyroradii of particles, we have information on the energy of the particles responsible for establishment of the wave layer. Given a magnetic field of 10^{-6} G, we would conclude that protons with Lorentz factors of order 1000 must play an important role in formation of the upstream wave layer.

Finally, we wish to remark briefly on the general utility of our technique for studies of interstellar turbulence. From Table 1, we see that our observations are sensitive to turbulence with $C_N^{\,2} Z_{\rm pc} \gtrsim 10$. Although pulsar observations, such as decorrelation bandwidth measurements, are capable of detecting more tenuous turbulence, 31 of the 76 pulsars studied by Cordes, Weisberg, and Boriakoff (1985) had $C_N^{\,2}\ Z_{\rm pc}$ in excess of 10. For a given direction, the line of sight to an extragalactic radio source will obviously pass through more turbulence than that to a pulsar, and more scattering will result. Measurements of extragalactic sources can also investigate the asymmetry of angular broadening and thus constrain the isotropy of irregularities and the role of refracting irregularities. As discussed above, there is the indication of such asymmetry in the case of 2013 + 370. In summary, multifrequency VLBI observations of extragalactic radio sources can provide important information on interstellar plasma turbulence.

IV. CONCLUSIONS

1. VLBI observations at 610, 1663, and 4991 MHz have been made of five compact sources whose lines of sight pass close to the edge of a galactic supernova remnant. These observations were primarily intended to search for angular broadening due to electron density turbulence induced by cosmic-ray–generated Alfrén waves upstream of the SNR shock.

2. The source 2013 + 370, which lies close to the Crab-like SNR G74.9 + 1.2, definitely shows scattering due to plasma turbulence. The observed broadening is 15–20 mas at 1.67 GHz and shows a λ^2 dependence. At the present time, it is not clear whether the scattering material is associated with the supernova remnant or with the closer "Cygnus superbubble" complex.

3. The source 1849 + 005, which lies in the vicinity of the SNR G33.6 + 0.1, did not produce detectable VLBI fringes. A probable explanation is very heavy interstellar scattering, corresponding to at least 0ʺ35 at 1 GHz. This scattering probably results from a line of sight which passes through the inner galaxy, rather than any single object.

4. Upper limits of about 8 mas or less at 1 GHz were established for turbulent broadening of the sources 0016 + 731, 0503 + 467, and 3C 418, associated with the supernova remnants CTA 1, HB 9, and HB 21, respectively.

5. These upper limits imply that if the cosmic-ray–induced turbulence possesses a Kolmogoroff spectrum, and is distributed over about 10 pc along the line of sight, the outer scale is larger than about 10^{14} cm.

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JOHN M. BENSON: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

JAMES M. CORDES: Astronomy Department, Cornell University, Space Sciences Building, Ithaca, NY 14850

ROBERT L. MUTEL and STEVEN R. SPANGLER: Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242