The Nature of 3C 391

A. H. Bridle and M. J. L. Kesteven
Astronomy Group, Department of Physics, Queen's University at Kingston, Ontario, Canada
(Received 29 July 1971; revised 2 September 1971)

Observations of the neutral-hydrogen absorption profile and microwave continuum emission of 3C 391 are presented. The classification of the source as a supernova remnant is supported, and the nature of its unusual radio continuum spectrum is discussed. The spectrum is most simply explained by postulating that the radiation from the source passes through an H II region situated between 3C 391 and the Sun. Alternative mechanisms, intrinsic to the source, are also discussed. We suggest five experiments which may provide further understanding of the spectrum.

The extended radio source 3C 391 (G31.9+0.0) has been shown to be nonthermal on the evidence of its 178-MHz surface brightness temperature of >50 000°K (Holden and Caswell 1969) and of its spectral index of ~0.5 between 408 MHz and 5 GHz (Milne 1969). Milne (1970) further classified the source as a galactic supernova remnant. The radio continuum spectrum of 3C 391 (Fig. 1) is, however, unusual for a supernova remnant: the flux density attains a maximum near 400 MHz. We have observed the neutral-hydrogen absorption profile of 3C 391, and its continuum emission at 6.63 and 10.63 GHz, to test the hypothesis that the source is a supernova remnant and to assist interpretation of its unusual spectrum.

After our study was initially reported (Kesteven and Bridle 1971), Caswell *et al.* (1971, henceforth referred to as CDGRG) published new observations of 3C 391 at 80 and 408 MHz, and a neutral-hydrogen absorption profile of the source in substantial agreement with our own. In this paper, we discuss the nature of 3C 391 in the light of all the recent observations: combination of our data with that of CDGRG suggests a new interpretation of the continuum spectrum.

I. 3C 391 AS A SUPERNOVA REMNANT

Studies of supernova remnants at known distances have suggested a correlation between their surface brightness temperatures and their linear sizes (Kesteven 1968b; Milne 1970). In Fig. 2 we plot these parameters at 1 GHz for selected remnants for which reliable distances are known either from optical proper-motion studies or from association of the radio remnants with emission nebulae at known distances in the Galaxy or in the Magellanic Clouds. The points representing Cas A, N132D, N63A, IC 443, HB3, and the Cygnus Loop lie on a line interpreted by Kesteven and by Milne as an evolutionary track for a "typical" radio remnant. If 3C 391 lay on this track, its 1-GHz brightness temperature of ~1000°K would imply a mean linear radius of 5.2 pc; its observed mean angular radius of ~1.7 arc min would correspond to a distance of ~10.5 kpc. There are three notable deviations from this track: the Crab Nebula, which is a unique object and will not be considered further, and the large overluminous remnants W49B and N49. The latter are almost identical objects with brightness temperatures

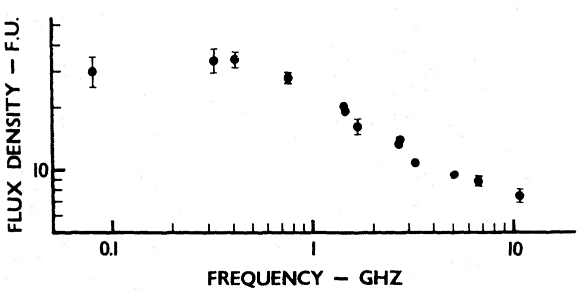

Fig. 1. The continuum spectrum of 3C 391 between 80 MHz and 10.63 GHz. The selection of the low-frequency data is discussed in Sec. II of the text. The 5-GHz point is the mean of three measurements.

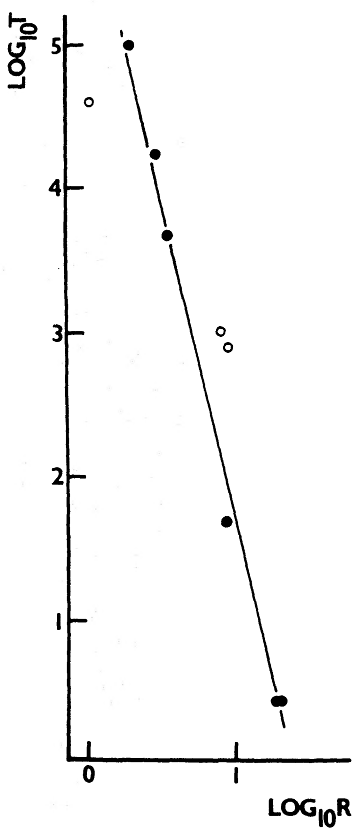

Fig. 2. Logarithmic plot of surface brightness temperature T in °K against mean linear radius R in parsecs for selected supernova remnants: *Filled circles* denote the remnants listed in Sec. I of the text. *Open circles* denote the Crab Nebula (*upper left*) and the large overluminous remnants W49B and N49 (see text).

of 1000 and 780 °K at 1 GHz, and mean linear radii of 8 and 9 pc, respectively. If 3C 391 were similar to these remnants, its distance would be ~18 kpc. We consider that 3C 391 could satisfactorily be classified as a supernova remnant if its distance were in the range 10.5 to 18 kpc.

Figure 3 shows the neutral-hydrogen absorption profile of 3C 391 obtained by us using the 300-ft transit telescope and 100-channel digital autocorrelation spectrometer of the National Radio Astronomy Observatory (operated by Associated Universities, Inc., under contract with the National Science Foundation). The equipment, observing procedure, and method of data reduction have been described elsewhere (Bridle and Kesteven 1970). The method of deriving the absorption profile, which is similar to that of Kerr and Knapp (1970), permits us to estimate quantitatively the uncertainties due to receiver noise and to confusing spatial fluctuations in the neutral-hydrogen emission at each velocity.

The uncertainties due to noise and confusion are small compared with the main features of the profile at all positive radial velocities. Further observations were made with the telescope offset in declination so that its response to the continuum from 3C 391 was reduced by one-half: these absorption features were all found to be reduced by one-half in these observations, confirming their reality.

In contrast, confusion at negative radial velocities leads to large uncertainties in the −17-km/sec feature, and this feature is probably unreal: it is not confirmed by CDGRG. Kerr and Knapp (1970) found absorption near this velocity in the spectra of the neighboring H II regions W43 (G30.8−0.0) and AMWW 50(G28.7 +0.1), which are at distances of ~7 kpc. There is evidently local material in these directions with appreciable noncircular motions, causing absorption near −17 km/sec. On both of these grounds, we reject the −17-km/sec feature of our profile as a distance indicator for 3C 391.

Both our data and that of CDGRG show significant absorption extending to the most positive radial velocities observed in emission in this direction, implying that 3C 391 lies beyond the rotational tangent point, i.e., at ≳8.5 kpc from the Sun. There appears to be little evidence to support the suggestion of Kerr and Knapp (1970) that 3C 391 may be in the same region of space as W43. The absorption profile alone cannot exclude the possibility that 3C 391 is extragalactic, but if its galactic latitude of 0°.0 and large angular extent are taken as sufficient evidence that it is galactic, an upper limit to its distance can be estimated from the kinematic distance of the most negative-velocity (~−45 km/sec) *emission* feature observed in its direction. On this basis, we estimate a distance between 8.5 and 21 kpc for 3C 391, consistent with the conclusion of CDGRG, and with the range of 10.5 to 18 kpc estimated above from comparing 3C 391 with established supernova remnants. It is therefore plausible to continue to classify 3C 391 as a supernova remnant, and important to explain its unusual continuum spectrum.

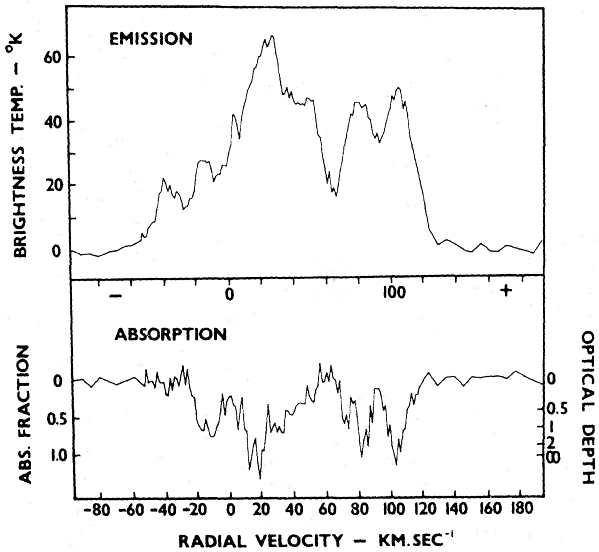

FIG. 3. Neutral-hydrogen emission and absorption profiles in the direction of 3C 391, observed with ~11-arc-min angular resolution and 6.25-kHz channel bandwidth. The data for velocities <−50 km/sec and >+120 km/sec were obtained at 25-kHz channel bandwidth. The emission profile has not been corrected for the effects of the error beam of the telescope.

TABLE I. Low-frequency continuum spectrum of 3C 391.

Frequency (MHz)	Corrected flux density (f.u.)	Correction factor applied	Original reference
80	30 ±5	×1.10	Caswell *et al.* 1971
85.5	20	×1.00	Mills *et al.* 1958
86	37.1 ±2.8	×0.94	Artyukh *et al.* 1969
178	28.3	×1.18	Bennett 1962
178	19.3 ±2.0	×1.09	Gower *et al.* 1967
178	18.5	×1.09	Holden and Caswell 1969
318	34 ±5	×1.00	Condon 1971
408	30 ±4.5	×1.10	Kesteven 1968a
408	34.4 ±3	×1.00	Caswell *et al.* 1971

II. THE LOW-FREQUENCY CONTINUUM SPECTRUM OF 3C 391

CDGRG summarize published data on 3C 391 at frequencies below 500 MHz, referred mainly to the CKL scale (Conway *et al.* 1963). Recent absolute flux-density measurements at 22.25 MHz (Roger *et al.* 1971), 26.3 MHz (M. Viner, private communication), and 81.5 MHz (Kellermann *et al.* 1969; J. R. Shakeshaft, private communication) have shown that the CKL scale systematically underestimates flux densities at 81.5 and 178 MHz. We have converted the low-frequency data listed by CDGRG to the scale of Roger *et al.* by applying the correction factors shown in

TABLE II. Free–free absorption models of the spectrum of 3C 391.

Frequency (MHz)	Flux density (f.u.) Observed	Interposed H II[a]	Internal H II[b]
80	30 ±5	21.6	25.9
318	34 ±5	40.9	40.2
408	34.4 ±3	37.0	36.6
750	28.1 ±1.5	27.6	27.6
1400	20.2 ±0.5	20.0	20.2

[a] Model parameters $\tau_{80}=1.5$, $T_K=8000°K$, $\alpha=0.56$.
[b] Model parameters $\tau_{80}=3.5$, $T_K=5000°K$, $\alpha=0.56$.

Table I, which also contains a new observation of 3C 391 at 318 MHz (Condon 1971). There is poor agreement among the low-frequency data. This can largely be attributed to the difficulties encountered by observers using fan-beam instruments and interferometers (see Table 1 of CDGRG) in allowing for gradients in the galactic background radiation and for the proximity of other intense sources. We therefore restrict our discussion to those total-power measurements which have angular resolution most capable of distinguishing 3C 391 from background confusion without appreciably resolving the emission from the source itself. These are the CDGRG data at 80 and 408 MHz, and that of Condon at 318 MHz; it is these data which are shown in Fig. 1.

The situation at 178 MHz is unclear: the measurement by Holden and Caswell, which should be the most reliable, would imply that 3C 391 has a complex spectrum. As the position and equivalent diameter of the source are unchanged within experimental uncertainties over more than two decades in frequency (see Sec. III B), this is unsatisfactory. CDGRG placed an upper limit on the 178-MHz flux density by correcting the 4C interferometric measurement (Gower *et al.* 1967) for resolution, using the visibility amplitudes measured at 1425 MHz by Fomalont (1967). This correction, amounting to 270%, cannot be determined reliably: its use requires the assumption that the source has identical visibility functions when observed with dissimilar interferometers at substantially different frequencies in a confused region of the galactic plane containing both thermal and nonthermal confusing emission. In view of these difficulties, we have not used the 178-MHz data to define models of the spectrum.

III. THE CONTINUUM SPECTRUM: ABSORPTION ON THE LINE OF SIGHT

The continuum spectrum of 3C 391 would not preclude interpreting the source as a "typical" supernova remnant if the decrease in flux density below 400 MHz could be attributed to free–free absorption by interstellar electrons along the line of sight to the source. Similar spectral features are found in other galactic continuum sources below ~20 MHz (e.g., Bridle 1969), and the spectral index of 3C 391 above 1 GHz is close to the mean index of ~0.5 characteristic of galactic supernova remnants at such frequencies (e.g., Shaver and Goss 1970). We therefore examine models of the distribution and temperature of interstellar material which might account for the observed decrease.

Free–free absorption in an intervening medium imposes a characteristic shape on the spectrum of a source, if the underlying nonthermal spectral index is constant with frequency. This shape is only weakly dependent on the temperature of the absorbing medium. For the observed high-frequency spectral index of 0.56, and an assumed temperature of 8000°K in the medium, this shape provides a poor, but not unreasonable, fit to the low-frequency spectrum of 3C 391 (Table II) if the line-of-sight optical depth at 80 MHz (τ_{80}) = 1.5. This value has been used, together with Scheuer's (1960) expression for the linear absorption coefficient of an ionized plasma, in determining the interstellar parameters discussed below.

A. Absorption in a Diffuse Medium

We first consider interpreting the spectrum in terms of free–free absorption in a diffuse medium distributed over most or all of the line of sight to 3C 391. As such a medium should not be peculiar to this line of sight, we assume it also to be present on the adjacent lines of sight through the Galaxy. The diffuse low-frequency absorption discussed by Bridle and Venugopal (1969) would have an optical depth of only 0.004 kpc^{-1} at 80 MHz, averaged over spiral-arm and inter-arm regions of the galactic disk. On a line of sight ~10 kpc long, this would be inadequate by a factor of ~40 to account for the observed decrease in flux density of 3C 391. As the line of sight to 3C 391 passes within 5.3 kpc of the galactic center, where the interstellar electron density may exceed that in the region studied by Bridle and Venugopal, it is also important to consider observations of the interstellar medium on this particular line of sight. Altenhoff *et al.* (1969) surveyed this area of the galactic disk with 10-arc-min resolution at 1.4, 2.7, and 5 GHz. At these frequencies, a diffuse electron gas with $\tau_{80}=1.5$ would appear in emission unless its characteristic temperature were low. The data of Altenhoff *et al.* place an upper limit of ~0.2°K on the 5-GHz brightness of any diffuse thermal component of the background radiation near 3C 391, which in turn implies an upper limit of ~800°K on the characteristic temperature of the hypothetical medium with $\tau_{80}=1.5$. At very low frequencies, a medium at this temperature would appear in absorption against the nonthermal galactic background: a line of sight with $\tau_{80}=1.5$ would have a 10-MHz optical depth $\tau_{10}\sim110$. Again taking the distance to 3C 391 as ~10 kpc, such a medium would impose an observational "horizon" ~200 pc from the Sun on 10-MHz observations in this direction. Taking the 10.03-MHz emissivity of the galactic disk as ~10^{-40} W m^{-3} sr^{-1} Hz^{-1} (Bridle 1968), such a model would predict a 10-MHz brightness temperature $<15\,000°$K in the direction of 3C 391. Preliminary observations by Purton *et al.* (1970) of a brightness temperature $\sim 550\,000°$K at 10.03 MHz in this direction are thus completely at variance with any diffuse absorption model compatible with the high-frequency data, unless the emissivity of the first 200 pc of the galactic disk in this direction is ~ 40 times that derived by Bridle. The same conclusion can be reached from analysis of the 19.7-MHz survey by Shain *et al.* (1961) in this area of the sky. We therefore discard the diffuse absorption interpretation of the spectrum, together with any interpretation involving large numbers of discrete ionized regions whose galactic distribution would approximate a diffuse absorption model.

B. Absorption in a Discrete Gas Cloud

If the spectrum were due to free–free absorption in a discrete ionized cloud with an angular diameter <10 arc min, the above contradictions would be removed, for the absorbing material would not appreciably fill the reception patterns of the telescopes used to study the line of sight; its high-frequency emission and low-frequency absorption would therefore not have been detected. The hypothetical cloud might be an H II region, i.e., gas at a kinetic temperature $\gtrsim 3000°$K, or a partially ionized H I region at a lower kinetic temperature. If the temperature of the absorbing material were sufficiently high, its free–free emission might be detectable at microwave frequencies. We therefore observed 3C 391 at 6.63 and 10.63 GHz using the 150-ft telescope at the Algonquin Radio Observatory (operated as a national radio astronomy facility by the National Research Council of Canada).

The observations were made in cloudless conditions with single-beam Dicke-switched radiometers, to provide reliable integrated flux densities for 3C 391, which was appreciably resolved at both frequencies. Table III lists the angular resolutions used and the integrated flux densities obtained in linear polarization at position angle 0° at each frequency. The flux densities are also plotted in Fig. 1.

The results at 10.63 GHz provide the highest-resolution full-beam map of 3C 391 presently available (shown in Fig. 4). The distribution of the 10.63-GHz emission is closely similar to that observed by CDGRG

TABLE III. Integrated flux densities of 3C 391 at microwave frequencies.

Frequency (GHz)	Resolution (arc min) α	δ	Flux density (f.u.)
6.63	3.74	3.95	9.0 ± 0.5
10.63	2.75	2.8	7.6 ± 0.6

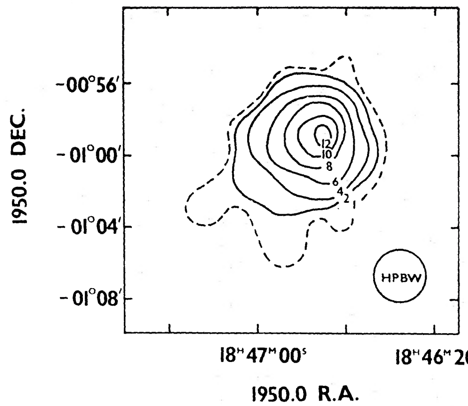

FIG. 4. Isophotes of 3C 391 at 10.63 GHz with 2.75- by 2.8-arc-min angular resolution: One contour unit is equivalent to 0.19 f.u.; the corresponding brightness temperature scale has not been determined accurately. The broken isophote is of low reliability.

at 408 MHz with slightly less resolution in declination. The peak intensity at 10.63 GHz occurs at $\alpha_{1950} = 18^h46^m46^s \pm 1^s$, $\delta_{1950} = -00°59'00'' \pm 15''$, in good agreement with the positions of the peak intensity reported by these authors at both 408 and 80 MHz. We have not derived a flux density for the "component" ~ 3.3 arc min in diameter proposed by CDGRG, as it cannot be identified in our data.

Strip scans through the CDGRG 408-MHz map of the source were compared directly with the individual right-ascension and declination scans made at 10.63 GHz in the preparation of our map. No evidence was found for any significant variation in the 408-MHz to 10.63-GHz spectral index across the source, but a more sensitive mapping at the higher frequency would be desirable to confirm this result.

Extrapolation to 10.63 GHz of the power law fitted to the spectrum of 3C 391 between 750 MHz and 5 GHz by a least-squares procedure predicts a flux density at this frequency of 6.5 ± 0.2 f.u. The observed flux density of 7.6 ± 0.6 f.u. thus represents an "excess" of 1.1 ± 0.6 f.u. which could readily be explained if the cloud responsible for the low-frequency absorption were an H II region. A region with $\tau_{80} = 1.5$ superimposed on the source would contribute this excess flux density if its kinetic temperature were $8000° \pm 4500°$K. These parameters require the emission measure to be 17 000 (+15 000; −12 000) pc cm^{-6}. Such values of the kinetic temperature and emission measure are entirely plausible for a galactic H II region. CDGRG comment on the failure of Reifenstein *et al.* (1970) to detect the H 109α recombination line in the direction of 3C 391, and suggest that this may be inconsistent with presuming an H II region to be responsible for the low-frequency continuum spectrum. The parameters derived above predict an H 109α line-to-continuum ratio of 3.5% for the H II region alone, assuming a "typical" line width (Reifenstein *et al.* 1970) of 30 km/sec. In the presence of the nonthermal continuum from the supernova remnant, the *over-all* H 109α line-to-continuum ratio for 3C 391 would be 0.45%, which is a factor ∼5 below the upper limit set by Reifenstein *et al.* (1970): the present recombination-line data do not, therefore, exclude the above interpretation of the continuum spectrum.

This discussion rests heavily on the inference of an "excess" flux density of ∼1.1 f.u. at 10.63 GHz, which could be in error if the nonthermal spectral index of 3C 391 decreased above 5 GHz, or if our 10.63-GHz integrated flux density were overestimated. There is insufficient information on the "typical" spectral properties of supernova remnants at high frequencies to exclude the former possibility. The high value of our flux density relative to the extrapolated spectrum is, however, supported by that of Zimmermann (1970) at 10.69 GHz, who obtained 8.5 ±0.6 f.u. from observations with 5-arc-min resolution. Zimmermann's result is the mean of flux densities determined in two orthogonal polarizations; the small discrepancy with our value could thus be due to linear polarization in the source. It is anyway within the relative uncertainties in our calibration scales. But for the poor fit to the present low-frequency data, it appears plausible to interpret 3C 391 as a "typical" supernova remnant whose radiation passes through an H II region along the line of sight.

A similar interpretation assuming a partially ionized H I region is implausible. For an assumed kinetic temperature of 125°K, the emission measure required by $\tau_{80}=1.5$ is 65 pc cm^{-6}, which in a standard cloud 10 pc in diameter would require a mean electron density $n_e=2.5$ cm^{-3}. We are aware of no heating mechanism capable of maintaining such a high electron density in interstellar hydrogen at this temperature. Even if the temperature were assumed to be as low as 25°K, near the lower limit of observed cloud temperatures in the Galaxy, the required electron density would be $n_e=0.9$ cm^{-3}, ∼20 times greater than the highest electron density calculated for this temperature by Spitzer and Scott (1969) assuming cosmic-ray heating.

C. Absorption in More Than One Discrete Gas Cloud

The assumption that a number of H II regions lie along the line of sight to 3C 391 would provide as satisfactory an explanation for the continuum spectrum as that obtained in Sec. III B for a single H II region.

CDGRG consider the most probable explanation of the low-frequency continuum spectrum to be free–free absorption in a number of discrete partially ionized H I clouds. They propose a model in which clouds with $n_e\sim 0.4$ cm^{-3} at a kinetic temperature of 50°K occupy 1% of the line of sight, and suggest that such ionization could be maintained by cosmic-ray heating. We consider this model implausible for the following reasons.

The CDGRG model provides the poor fit below 500 MHz common to all of the line-of-sight free–free absorption models, but in addition the model appears to require unrealistic parameters of the interstellar clouds. Recent discussions of the heating of H I regions at interstellar densities (Spitzer and Scott 1969; Habing and Goldsmith 1971) suggest that neither cosmic-ray nor soft x-ray heating could maintain an electron density as high as 0.4 cm^{-3} in interstellar hydrogen at 50°K. CDGRG also suggested that the material responsible for the low-frequency absorption might be identified with the clouds seen in absorption against 3C 391 in the 21-cm line. We have used the 21-cm absorption profiles observed by CDGRG and by ourselves, together with the heating theory of Spitzer and Scott, to estimate the emission measures of these clouds. The emission measure obtained for a cloud temperature of 50°K is 0.4(+0.5; −0.2) pc cm^{-6}, much less than the 20 pc cm^{-6} required to provide $\tau_{80}=1.5$ at this temperature; a similar discrepancy is found for cloud temperatures of 25 and 150 °K. The major source of uncertainty in these calculations is the inability of the 21-cm line measurements to determine the largest optical depths accurately; we therefore made the assumption, favorable to the CDGRG suggestion, that $\tau=10$ within each of the deep 21-cm absorption features.

IV. THE CONTINUUM SPECTRUM: MECHANISMS INTRINSIC TO THE SOURCE

The most promising of the explanations for the spectrum discussed in Sec. III is that of an H II region or regions interposed along the line of sight to 3C 391. As this provides only a poor fit to the data below 500 MHz, mechanisms intrinsic to the source have also been considered.

A. Synchrotron Self-Absorption

Fomalont (1967) showed that <10% of the flux density of 3C 391 at 1425 MHz arises from structure ≲15 arc sec in apparent diameter. It is therefore unlikely, as pointed out by CDGRG, that synchrotron self-absorption could be responsible for the observed spectrum.

B. Free–Free Absorption within the Source

Free–free absorption by thermal electrons within the emitting regions of a nonthermal source attenuates the flux density less rapidly with decreasing frequency than does the line-of-sight absorption considered in Sec. III. The exact form of the predicted low-frequency spectrum depends on the relative distribution of the thermal electrons and the nonthermal emissivity, which in the case of 3C 391 is unknown. If it is assumed, for convenience, that the thermal and nonthermal particles are fully mixed, the predicted low-frequency spectrum (Table II) provides a good fit to the data for

3C 391 if the 80-MHz optical depth of the absorbing material on a typical line of sight through the source is $\tau_{80}=3.5$. For a kinetic temperature $\sim$5000°K in the absorbing material, this model also provides a satisfactory fit to the spectrum at 5 GHz and above.

In terms of the goodness of fit to the present spectral data, this interpretation appears preferable to that of an interposed H II region. The emission measure required on a typical line of sight through the source is $\sim$20 000 pc cm^{-6} at 5000°K, which requires the average electron density along a line of sight to be $45\xi^{\frac{1}{2}}$ cm^{-3}, where ξ is the filling factor for the thermal plasma. At the assumed distance of $\sim$10 kpc, this requires a total mass of ionized material of $660\xi^{\frac{1}{2}}$ solar masses. This is incompatible with interpreting 3C 391 as a normal supernova remnant unless ξ is very small, as in a filamentary distribution. For the total mass of ionized material to be <10 solar masses, ξ must be $<2.3\times10^{-4}$, implying a scale size $<2.3\times10^{-3}$ pc and $n_e \gtrsim 3000$ cm^{-3} for the electron concentrations. These parameters are within an order of magnitude of the properties of the optical filaments in other supernova remnants (e.g., Osterbrock 1957; Harris 1962; Minkowski 1964). Obscuration prevents optical investigation of the ionized material in 3C 391, and it may not be appropriate to compare these requirements with conditions in the filaments of visible supernova remnants, which do not have radio continuum spectra similar to that of 3C 391. The physical plausibility of this interpretation is therefore difficult to assess. It would be more difficult to sustain if 3C 391 were at a distance $\sim$18 kpc, for the required mass of ionized material would then be $\sim2500\xi^{\frac{1}{2}}$ solar masses.

An alternative to postulating a filamentary distribution of the ionized material would be to assume that the supernova explosion occurred in a region of enhanced interstellar density.

C. The Tsytovich–Razin Effect

The low-frequency data could plausibly be fitted by a Tsytovich–Razin spectrum with a critical frequency (Scheuer and Williams 1968) of $\sim$60 MHz. This would require a magnetic field strength in the source of $B(\mu\text{gauss})=0.25n_e$, where n_e is the mean electron density in cm^{-3}. An upper limit to n_e can be provided by assuming the remnant to contain $\lesssim10$ solar masses of fully ionized hydrogen, in which case $n_e\lesssim0.8$ cm^{-3}. Thus $B\lesssim0.2$ μgauss, which would imply a total energy in relativistic particles $>4\times10^{53}$ ergs, assuming a distance of $\sim$10 kpc and a proton/electron ratio of 100:1. As this is $\sim$400 times the expansion energy of most supernova remnants, it is unlikely that the Tsytovich–Razin effect is responsible for the observed spectrum.

D. Deficiency of Low-Energy Electrons in the Source

A total absence of low-energy electrons in the source would produce a low-frequency continuum spectrum of the form $S\propto\nu^{0.33}$; the spectrum defined by the 80-, 318-, and 408-MHz data is $S\propto\nu^{0.09\pm0.15}$, so the low-frequency data could be explained by postulating a deficiency of electrons within the source below some critical energy. This interpretation, which is the only one consistent with the 178-MHz flux density of Bennett (1962), was also proposed by CDGRG. Its plausibility is again difficult to assess, since little is known of the mechanisms by which relativistic electrons are generated in supernova remnants, or of processes which might lead to a deficiency of low-energy electrons in one remnant and not in another.

V. DISCUSSION AND CONCLUSIONS

Three interpretations of the unusual spectrum of 3C 391 justify further consideration. Of these, the mechanisms intrinsic to the source (internal free–free absorption and a deficiency of low-energy electrons) provide better fits to the low-frequency data than does the line-of-sight absorption mechanism. The latter, however, invokes a galactic H II region with a "typical" electron density and kinetic temperature in order to account for the spectrum, while the former require specific, and largely unverifiable assumptions about 3C 391 itself. As the present low-frequency data are relatively inaccurate, goodness of fit is only a weak criterion for the suitability of a model. We therefore suggest that an interposed H II region is the most probable explanation for the spectrum, particularly as the line of sight to 3C 391 passes at $b=0\overset{\circ}{.}0$ through the annulus of the Galaxy within which H II regions are particularly abundant. On this interpretation, 3C 391 could be regarded as a "typical" supernova remnant. Our earlier rejection of this hypothesis (Kesteven and Bridle 1971) was based on the less accurate low-frequency data available prior to the work of CDGRG.

The following experiments may provide further understanding of the spectrum of 3C 391:

(i) Detailed mapping of the source over a range of frequencies with improved angular resolution and sensitivity. If the spectrum were due to free–free absorption in an interposed H II region, it is unlikely that the absorbing material and 3C 391 would have identical positions and angular structure. Variations in the spectral index across the source, or emission from the hypothetical H II region, might be detected by more sensitive mapping at microwave frequencies. It would also be desirable to confirm the "excess" flux density suggested by our work and that of Zimmermann (1970), and to establish whether or not the source has a shell structure.

(ii) Measurements of the rotation measure. As yet no polarization has been measured in 3C 391 (see CDGRG). The polarization properties of the source might be revealed by observations at microwave frequencies with instruments capable of resolving its structure. Useful constraints might then be placed on the interposed-H II and internal-H II models if the rotation measure (which should be large if these models were correct) could be determined across the source.

(iii) Accurate flux densities at low frequencies. An accurate flux density near 200 MHz could distinguish the electron-deficiency model from the others; this model predicts a flux density $\sim$32 f.u. near 200 MHz, whereas both the interposed-H II and internal-H II models predict $\sim$46 f.u. More decisive, but more difficult, measurements could be made at a frequency below 80 MHz but not so low that the flux density would be severely attenuated by the general interstellar absorption. At $\sim$50 MHz, for example, the electron-deficiency model would predict a flux density $\sim$29 f.u., the internal-H II model $\sim$14 f.u., and the interposed-H II model $\sim$3 f.u.

(iv) Observations of low-*n* recombination lines. Positive detection of a hydrogen recombination line in the direction of 3C 391 would favor the interposed-H II model. On the internal-H II model, the expected line width would be large, due to the internal motions of the remnant, and this would make a positive detection unlikely. On the interposed-H II model, the line width should be $\sim$30 km/sec. Studies of the low-*n* recombination lines would be most profitable, as the proportion of thermal-to-nonthermal emission from 3C 391 would increase with increasing frequency.

(v) Observations of the 21-cm absorption profile with narrow channel bandwidth. Such data could define more closely the parameters of the cold neutral-hydrogen clouds on the line of sight to 3C 391. If optical depths much greater than 10 were found in very cold (<50°K) clouds, the CDGRG model might be reconsidered.

Programs (i) and (ii) are in progress at the Algonquin Radio Observatory.

ACKNOWLEDGMENTS

We thank the Director of the National Radio Astronomy Observatory and the Programming Committee of the Algonquin Radio Observatory for granting telescope time for these observations, and the technical staff of both observatories for their assistance. We also thank D. G. MacDonell for assistance with the observations. This work was supported by operating grants from the National Research Council of Canada.

REFERENCES

Altenhoff, W. J., Downes, D., Goad, L. E., Maxwell, A., and Rinehart, R. 1969, *Astron. Astrophys. Suppl.* **1**, 319.
Artyukh, V. S., Vitkevich, V. V., Dagkesamanskii, R. D., and Koshukhov, V. N. 1969, *Sov. Astron. AJ* **12**, 567 [*Astron. Zh.* **45**, 712 (1968)].
Bennett, A. S. 1962, *Mem. Roy. Astron. Soc.* **68**, 163.
Bridle, A. H. 1968, *Monthly Notices Roy. Astron. Soc.* **138**, 251.
——. 1969, *Nature* **221**, 648.
Bridle, A. H., and Venugopal, V. R. 1969, *ibid.* **224**, 545.
Bridle, A. H., and Kesteven, M. J. L. 1970, *Astron. J.* **75**, 902.
Caswell, J. L., Dulk, G. A., Goss, W. M., Radhakrishnan, V., and Green, A. J. 1971, *Astron. Astrophys.* **12**, 271.
Condon, J. J. 1971, *Cornell-Sydney Univ. Astron. Centre Report*, No. 238.
Conway, R. G., Kellermann, K. I., and Long, R. J. 1963, *Monthly Notices Roy. Astron. Soc.* **125**, 261.
Fomalont, E. B. 1967, *Publ. Owens Valley Radio Obs.* **1**, No. 2.
Gower, J. F. R., Scott, P. F., and Wills, D. 1967, *Mem. Roy. Astron. Soc.* **71**, 49.
Habing, H. J., and Goldsmith, D. W. 1971, *Astrophys. J.* **166**, 525.
Harris, D. E. 1962, *ibid.* **135**, 661.
Holden, D. J., and Caswell, J. L. 1969, *Monthly Notices Roy. Astron. Soc.* **143**, 407.
Kellermann, K. I., Pauliny-Toth, I. I. K., and Williams, P. J. S. 1969, *Astrophys. J.* **157**, 1.
Kerr, F. J., and Knapp, G. R. 1970, *Australian J. Phys. Astrophys. Suppl.* (No. 18), 9.
Kesteven, M. J. L. 1968a, *Australian J. Phys.* **21**, 369.
——. 1968b, *ibid.*, 739.
Kesteven, M. J. L., and Bridle, A. H. 1971, paper presented at 1st Meeting of NRC Associate Committee for Astronomy, Victoria, British Columbia, May 13–15, 1971; *J. Roy. Astron. Soc. Canada* **65**, 177 (abstract).
Mills, B. Y., Slee, O. B., and Hill, E. R. 1958, *Australian J. Phys.* **11**, 360.
Milne, D. K. 1969, *ibid.* **22**, 613.
——. 1970, *ibid.* **23**, 425.
Minkowski, R. 1964, *Ann. Rev. Astron. Astrophys.* **2**, 247.
Osterbrock, D. E. 1957, *Publ. Astron. Soc. Pacific* **69**, 227.
Purton, C. R., Caswell, J. L., and Bridle, A. H. 1970, paper presented at *Symposium on Low-frequency Radio Astronomy*, June Meeting of Astron. Soc. Pacific, Penticton, British Columbia.
Reifenstein III, E. C., Wilson, T. L., Burke, B. F., Mezger, P. G., and Altenhoff, W. J. 1970, *Astron. Astrophys.* **4**, 357.
Roger, R. S., Bridle, A. H., and Costain, C. H. 1971, in preparation.
Scheuer, P. A. G. 1960, *Monthly Notices Roy. Astron. Soc.* **120**, 231.
Scheuer, P. A. G., and Williams, P. J. S. 1968, *Ann. Rev. Astron. Astrophys.* **6**, 321.
Shain, C. A., Komesaroff, M. M., and Higgins, C. A. 1961, *Australian J. Phys.* **14**, 508.
Shaver, P. A., and Goss, W. M. 1970, *Australian J. Phys. Astrophys. Suppl.* (No. 14), 133.
Spitzer, L., and Scott, E. H. 1969, *Astrophys. J.* **158**, 161.
Zimmermann, P. 1970, *Beiträge Radio-Astron.* **1**, 161.