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The Distance and Spectrum of 3C 391

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The angular structure and low-frequency spectrum of 3C 391 have been investigated with new high-resolution observations at 80 and 408 MHz. The spectrum has a turnover near 408 MHz. An H I absorption kinematic distance shows that the source is at least 8.5 kpc distant. The new data are compatible with the conclusion that 3C 391 is a supernova remnant.

Key words: 3C 391 — supernova remnant — distance — spectrum

Introduction

Earlier work on 3C 391 (G31.9 + 0.0) by Holden and Caswell (1969) and Milne (1969) has shown that the source is non-thermal, or at least contains a non-thermal component. The spectrum is unusual in that between 408 and 750 MHz there is a change of spectral index α (where $S \propto \nu^{\alpha}$) from approximately -0.6 at high frequencies to $+0.1$ at low frequencies.

In the present investigation we have defined more precisely the low-frequency end of the spectrum and have shown that the total angular size and mean position do not change over a wide frequency range. The low galactic latitude of 3C 391 strongly suggests it is a galactic object (e.g. Caswell, 1969) and consequently its distance is of considerable interest. We have used H I absorption techniques to determine a lower limit to the distance. Finally we discuss the hypothesis that 3C 391 is a supernova remnant in view of our distance limit and the low-frequency spectrum of 3C 391.

Observations of the Spectrum and Angular Structure

a) 408 MHz *Observations*

The region around 3C 391 was mapped at 408 MHz using the Mills Cross at Molonglo. The instrument has a halfpower beamwidth (HPBW) of 2'.86 E-W and 3'.47 N-S at the declination of 3C 391. A drift scan was made with 11 adjacent beams in declination, separated by 1'.73 arc and the 11 scans were combined to give the contour map of Fig. 1. These observations of 3C 391 are of higher resolution than any previous ones, and the structure of the source is seen to comprise an intense compact feature, within a weaker, more extended structure. The total intensity of 3C 391 is 34.4 ± 3 f.u. (where 1 f.u. = 10^{-26} W m^{-2} Hz^{-1}), obtained from integration over the whole source. (We have not included the very weak feature, ≈ 0.9 f.u., at $18^h46^m45^s$, $-00°51'$, since this is probably a sidelobe response or an unrelated source.) For the compact feature alone, we derived a flux density of 26.1 ± 3 f.u. and a position

$$18^h46^m46^s.7 \pm 1^s.0,\ -00°58'45'' \pm 10''.$$

The half-power width of a source, θ_s, may be estimated in terms of the half-power widths of the beam, θ_b, and the observed trace, θ_0; if gaussian approximations are used, $\theta_s = \sqrt{\theta_0^2 - \theta_b^2}$. For the compact feature this calculation yields source widths to half intensity of 3'.2 ± 0'.5 E-W and 3'.4 ± 0'.5 N-S.

b) 80 MHz *Observations*

The source flux density and angular size were measured at 80 MHz using the radioheliograph at Culgoora (Wild, 1967). The HPBW at the declination of 3C 391 is 4'.4 N-S by 3'.8 E-W. Our observations consisted of 16 drift scans of the source with seven beams separated by 2'.4 in declination. After smoothing with a time constant of 1^s, the data were sampled at a 2 Hz rate and recorded on magnetic tape. Subsequent computer processing produced averaged drift scans at each declination and a contour map of the source. The flux density was determined by integrating the flux under the contours and comparing it with observations of several standard sources given by Kellermann *et al.* (1969). Because we have not yet completed the analysis of all our standard sources,

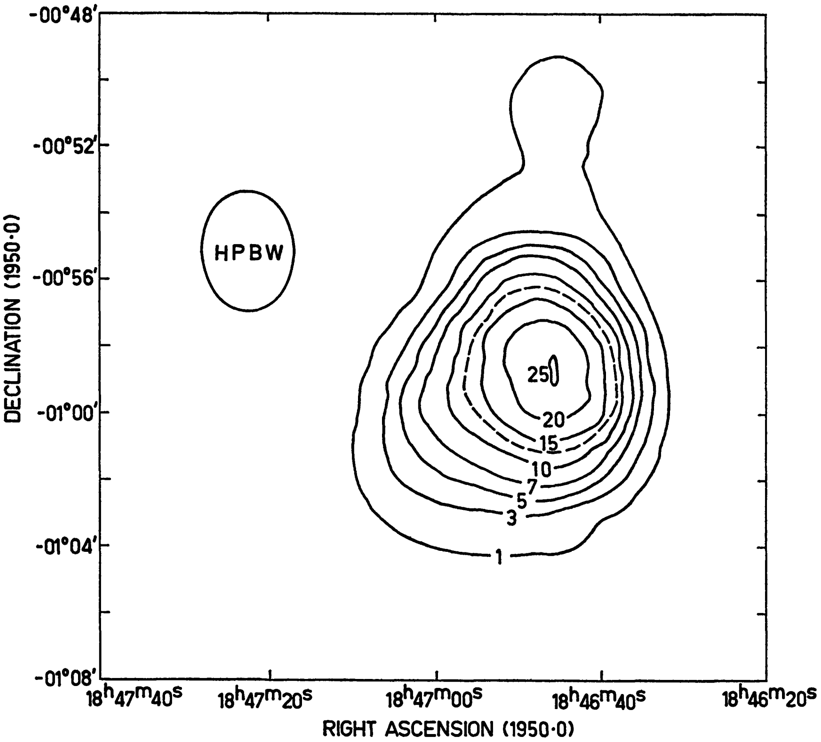

Fig. 1. 3C 391 at 408 MHz. 1 contour unit ≡ 100° K (T_b). The galactic background has been subtracted to indicate the adopted zero level for the source. The broken line is the half-intensity contour. The extension to the north of contour 1 may be a sidelobe response or an unrelated source

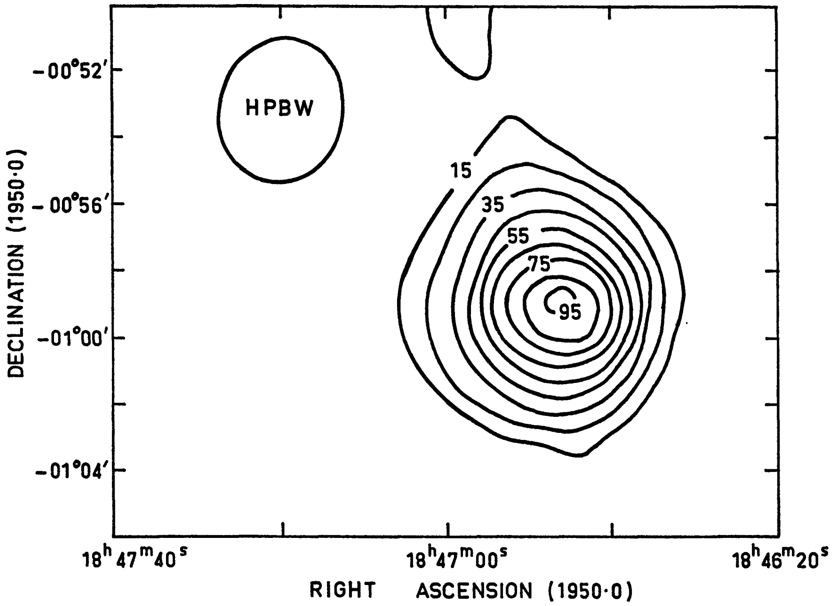

Fig. 2. 3C 391 at 80 MHz. Contours are marked at 15%, 25% ... 95% of the peak intensity. The instrument does not respond to very large-scale galactic structure, and the zero level is therefore arbitrarily chosen as the local mean level beneath the source

Table. *Measurements of flux density and angular size of* 3C 391

(1) Fre-quency MHz	(2) Half-power Beamwidth[a]) R.A.	Dec.	(3) Source Size (arc min) R.A.	(4) Dec.	(5) Flux Density (f.u.)	(6) Reference	(7) Notes
80	3′.8	4′.4	3.5	2.8	27 ± 5	This paper	Total integrated flux density; see text.
85.5	50′	60′			16	MSH 18−012 (1)	Flux density discussed in (6).
86	≈ 22′	4°.3			39.5 ± 3.0	(2)	Interferometer E-W lobe sepn. = 22′.
159	1°.2	7°.7			27 ± 6	3C 391 (3)	Interferometer E-W lobe sepn. = 11°.4. N-S lobe sepn. = 130′.
178	13′.6	4°.2			26	3CR 391 (4)	Flux density discussed in (6).
178	23′.4	52′			17.7 ± 1.8	4C−00.72 (5)	Interferometer E-W lobe sepn. = 7′.5.
178	23′.4	30′.6			17	HC 11 (6)	
408	1′.4	4°.2	3.6	—	27 ± 4.5	Kes 77 (7)	Point source flux density corrected for broadening.
408	2′.65	3′.46	3.6	2.9	27	(8)	Point source flux density corrected for broadening.
408	2′.86	3′.47	3.2	3.4	34.4 ± 3	This paper	Total integrated flux density; see text.
750	18′.5	18′.5			28.1 ± 1.5	NRAO (9)	See (10) for discussion.
1400	10′	10′	4.5	4.5	20.2 ± 0.5	NRAO (9)	See (10) for discussion.
1410	14′	14′			19[b])	(11)	
1410	14′	14′			17.8[b])	(12)	
1425	45″	33′			21.2	(13)	Total.
			2.5		15.5	(13)	Component A.
			2.0		3.6	(13)	Component B.
			0.3		2.1	(13)	Component C.
1667	12′	12′			16.4 ± 1.5	(14)	
2650	7′.4	7′.4			11[b])	(11)	
2650	11′	11′			13.6	(15)	See (10) for discussion.
2650	8′.3	8′.3			11.6[b])	(12)	
3200	8′.9	8′.9			11.0 ± 1	(16)	
5000	4′.0	4′.0	3.7	3.1	10.0 ± 0.8	(17)	
5000	6′.0	6′.0			10.1	(18)	
5000	6′.0	6′.0	3.7	2.4	9.4	(19)	
5000	4′.0	4′.0			9.8 ± 0.2	(20)	

[a]) For interferometers, primary beam pattern is quoted.
[b]) Peak flux.

References to the Table

(1) Mills *et al.*, 1958
(2) Artyukh *et al.*, 1969
(3) Edge *et al.*, 1959
(4) Bennett, 1962
(5) Gower *et al.*, 1967
(6) Holden and Caswell, 1969
(7) Kesteven, 1968
(8) Shaver, P.A. 1969, private communication
(9) Pauliny-Toth *et al.*, 1966
(10) Kellermann *et al.*, 1969
(11) Beard and Kerr, 1969
(12) Gardner *et al.*, 1969a
(13) Fomalont, 1968
(14) Goss, W.M., unpublished data
(15) Kellermann *et al.*, 1968
(16) Caswell, J.L., unpublished data
(17) Milne, 1969
(18) Pauliny-Toth and Kellermann, 1968
(19) Reifenstein *et al.*, 1970
(20) Shimmins *et al.*, 1969.

we feel that the uncertainty in flux density is about 20%.

The flux density of 3C 391 at 80 MHz was found to be 27 ± 5 f.u. Figure 2 shows the contour map of 3C 391. The extensions in the N-S direction probably represent a sidelobe or possibly the system responding to numerous weak sources in the grating lobes of the radioheliograph. The observed source position $18^h46^m46^s.5 \pm 4^s$, $-00°58'.9 \pm 1'$, is within $0'.2$ of the 408 MHz position. This excellent agreement may be fortuitous because deviations of 1′ to 2′ can be caused at 80 MHz by ionospheric refraction even under the

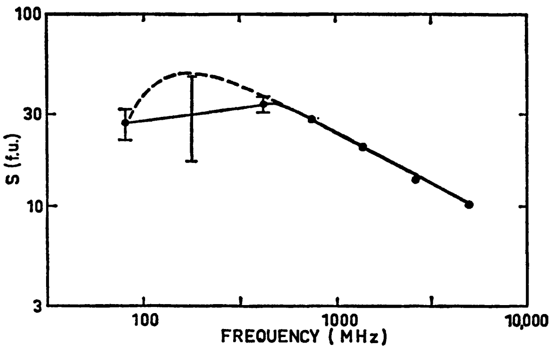

Fig. 3. Continuum spectrum of 3C 391. The solid line represents a fit to the data using only two spectral indices of −0.57 between 5000 and 750 MHz and of +0.13 between 408 and 80 MHz. The broken line shows the predicted spectrum corresponding to free-free absorption in the intervening medium as discussed in the text

good conditions existing when the present observations were made; the source observed just prior to 3C 391 was displaced 1′ from its published position.

The source size approximated by a gaussian is 3′.5 ± 1′.0 E-W by 2′.7 ± 1′.5 N-S (half-power widths after allowing for the beam size).

c) *The Position and Angular Structure*

Our positions measured at 80 and 408 MHz agree well with the value of $18^h46^m47^s$, $-00°58'.7$ derived by Milne (1969) from slightly lower resolution observations at 5000 MHz. In addition, to within the resolution limits of the observations the source has the same size over the frequency range 80 to 5000 MHz (see Table 1). From interferometer observations, Fomalont (1968) has derived a model for the E-W structure at 1425 MHz, as seen with a fan beam 45″ (right ascension) × 33′ (declination). His model, with three components, indicates that although some fine structure is unresolved by our 408 MHz observations, less than 10% of the intensity originates from structure with size < 18″ whereas more than 70% arises from a compact feature with E-W width to half-intensity (equivalent gaussian) of 2′.5. Our 408 MHz observations smoothed to a 33′ beam in declination showed good agreement with Fomalont's model structure smoothed to a 2′.86 beam in right ascension, which provides further evidence that the structure is essentially unchanged over the frequency range 408 to 1425 MHz.

d) *The Spectrum*

In Table 1 we list the flux densities used to study the spectrum.

In Fig. 3 we show only the measurements of high angular resolution and omit values with large errors or peak fluxes measured with small beams. We also indicate an upper and lower limit at 178 MHz, as discussed below.

The region between 80 and 408 MHz is important for determining the spectral curvature, and in the absence of high resolution data we consider the available measurements in more detail. The angular size data at 80, 408 and 1425 MHz all indicate that partial resolution must have significantly reduced the intensities measured by the 4C and 3C interferometers (E-W lobe spacings of 7′.5 and 11′.4 respectively). We use Fomalont's (1967) interferometer measurements to estimate the corresponding visibility amplitudes, and derive flux densities corrected for partial resolution of 48 f.u. (4C at 178 MHz) and 42 f.u. (3C at 159 MHz). The 178 MHz pencil-beam intensity (Holden and Caswell, 1969) is no larger than the 4C uncorrected value, and we regard this as a firm lower limit to the 178 MHz flux density. We tentatively regard the 4C (corrected) value as an upper limit, although the implication that the pencil-beam value could be low by a factor of nearly 3 is surprising. The 3CR fan-beam measurement at 178 MHz lies between these limits.

From Fig. 3 we see that the spectral index above 750 MHz is −0.57; between 750 and 408 MHz the spectrum flattens, and below 408 MHz it is most simply represented by a constant spectral index, $\alpha \approx 0.13$, though the data do not preclude more complex features.

Distance of 3C 391

Figure 4 shows the 21 cm H I profiles in the direction of 3C 391. The emission profile (Fig. 4, upper profile) was obtained with the Parkes 64-m telescope (HPBW 15′) pointing at the source; although 3C 391 is in the beam, its antenna temperature is only 10° K and thus absorption of 3C 391 does not depress the measured emission by more than 10° K anywhere. The absorption profile (Fig. 4, lower profile) was obtained with the Parkes 21 cm line interferometer, which will be discussed in detail by Radhakrishnan *et al.* (in preparation). The primary beam size is 18′.5 and for this observation the lobe separation was ~ 7′ in position angle ~ 10°.

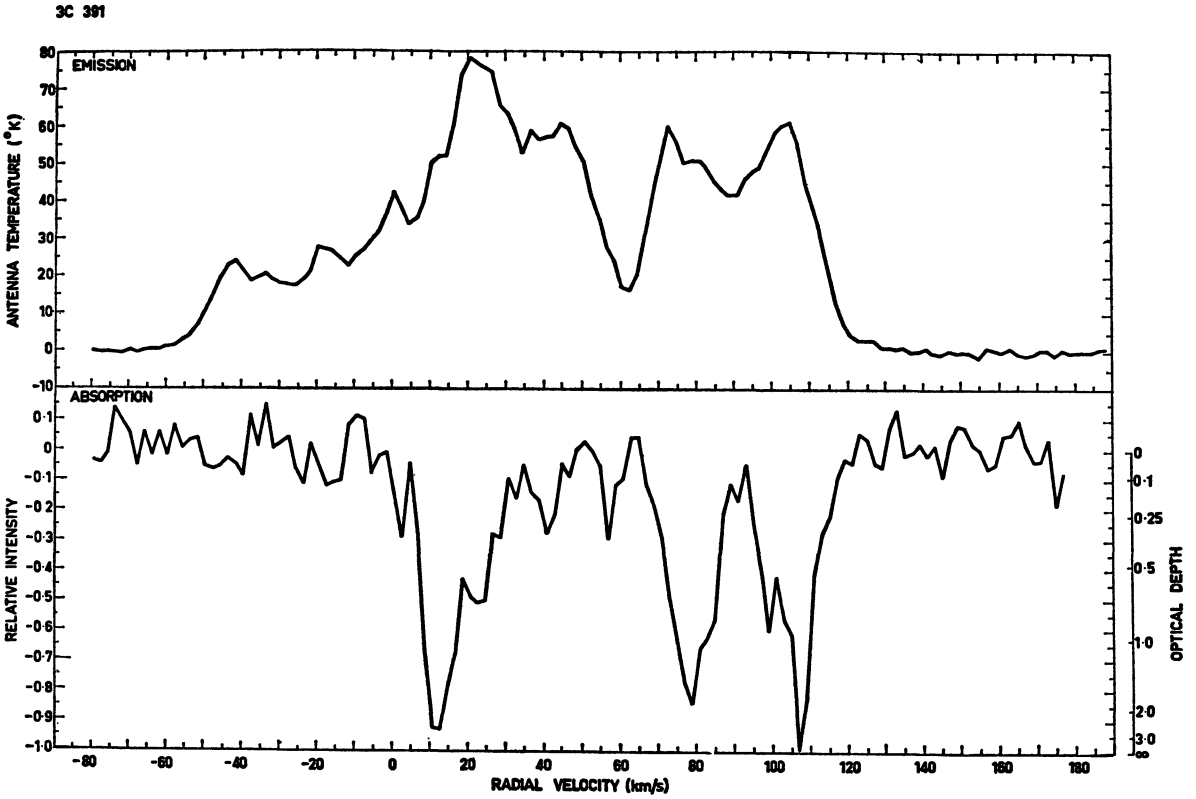

Fig. 4. 21 cm H I profiles in the direction of 3C 391. Upper profile (emission) was obtained with single dish, beamwidth 15′, pointing at source. Lower profile (absorption) was obtained with interferometer, primary beam size 18′5 and lobe separation 7′ in P.A. ≈ 10°; the relative intensity scale refers to fractional absorption, R.I. = − 1.0 $[1 - e^{-\tau(\nu)}]$

The emission shows five major concentrations with velocity ranges − 60 to 0 km s^{-1}, 0 to + 35 km s^{-1} + 35 to + 60 km s^{-1}, + 60 to + 90 km s^{-1}, and + 90 to + 115 km s^{-1}. Because a corresponding absorption feature exists in the range + 90 to + 115 km s^{-1} (the highest velocity seen in emission) we conclude that the source is located beyond the tangential point, 8.5 kpc distant (based on 10 kpc to the galactic centre). For such a large radial velocity, any peculiar velocities of up to 10 km s^{-1} would not significantly alter this conclusion.

There is no detectable absorption corresponding to the emission with velocities + 35 to + 60 km s^{-1}; using the Schmidt rotation curve, we find the two possible distances for this gas are ~ 3.7 and ~ 13.4 kpc. If we assume that all major H I concentrations in front of a source should show up in absorption, then we can say that the distance of the source is between 8.5 and 13.4 kpc. However, the absence of absorption in the direction of distant sources can only be interpreted as a necessary but not sufficient condition for the source to be beyond the hydrogen. In the direction of the source it is quite possible that no dense absorbing cloud exists; in addition, the hydrogen can be at a high kinetic temperature so that its optical depth is quite low.

The H I emission at negative velocities (0 to − 60 km s^{-1}) originates from regions beyond the solar circle at 17 kpc. The above remarks concerning the lack of absorption apply even more strongly for these large distances. We conclude that the source is definitely beyond 8.5 kpc and possibly closer than 13.4 kpc. However, the H I absorption measurements alone cannot preclude the possibility that 3C 391 is extragalactic.

The Nature of the Source

Milne (1970), on the assumption that 3C 391 is a supernova remnant and adopting an empirical relationship between radio surface brightness and linear dimensions for supernovae, derived a distance of 8.6 kpc for 3C 391. The agreement with our lower distance limit, 8.5 kpc, is striking but partly fortuitous, since Milne's curve is for an *average* supernova remnant and there is some dispersion about his mean curve. Nonetheless, the agreement confirms that our distance limit, taken in conjunction with the surface brightness and angular size, is compatible with 3C 391 being a typical supernova remnant, and strengthens arguments based on the very low galactic latitude, the non-thermal spectral index, and the extended brightness distribution. The high resolution 408 MHz observations confirm that the distribution is extended both E-W and N-S in a manner consistent with other known supernova remnants, though still higher resolution will be necessary to reveal any detail.

If the source is a supernova remnant, polarization would be expected; however, no significant polarization has yet been detected, probably because measurements made to date do not resolve the source. Gardner *et al.* (1969a, 1969b) quote $0.2 \pm 0.4\%$ at 1410 MHz, $0.4 \pm 0.4\%$ at 2650 MHz and $0.4 \pm 0.2\%$ at 5000 MHz.

We now consider possible explanations for the flattening of the spectrum near 408 MHz. The best estimate of the spectral shape suggests a change of slope $\Delta\alpha \approx 0.7$, whereas for most mechanisms the expected change of slope is considerably greater.

We first reject explanations which invoke several components of different spectral index. We infer that the source as observed above 750 MHz is non-thermal from its spectral index, and independently we may infer that the source as observed at 80 MHz is non-thermal from its high brightness temperature ($> 10^5$ °K). Thus there is no indication of a thermal component, and the failure to detect the hydrogen 109α recombination line (Reifenstein *et al.*, 1970) reinforces this conclusion. In addition, the position and angular size of the source do not change significantly over the whole observed frequency range, which strongly suggests we are observing essentially the same source at all frequencies. Furthermore, if we postulate a compound source to interpret the spectrum, we still cannot avoid the problem that one of the components must have an unusual spectrum.

We now consider separately mechanisms intrinsic to the source and thermal absorption in the intervening medium.

a) Mechanisms Intrinsic to the Source

The following mechanisms may give rise to a low-frequency cut-off in the radiation from a synchrotron emitter (e.g. Ginzburg and Syrovatskii, 1965).

(i) If there is a low energy cut-off in the electron energy spectrum, it will cause a corresponding cut-off in the low-frequency radiation.

(ii) Low-frequency radiation may be suppressed if the index of refraction deviates appreciably from unity (the Tsytovich-Razin effect).

(iii) Synchrotron self-absorption will occur if intense emission originates from regions of small physical size.

(iv) If there are thermal electrons mixed with the relativistic electrons they will cause free-free absorption at low frequencies.

For (i), the maximum allowed value of α at frequencies below the turnover is 1/3; the observed value for 3C 391, $\geqq 0.13$, is rather close to this limit, and implies that the cut-off in the electron energy spectrum, if it were responsible for the spectral curvature, would need to be extremely steep. Mechanism (iii) is probably ruled out by Fomalont's observations that very little of the emission originates from small-diameter features. Mechanisms (ii) and (iv) cannot be rejected without a more detailed knowledge of conditions within the source.

b) Free-free Absorption in the Intervening Medium

Milne (1969) has previously suggested that this is responsible for the low-frequency turnover in the spectrum of 3C 391. If we assume the intrinsic spectrum continues with $\alpha = -0.57$ to 80 MHz, the optical depth of the intervening medium at 80 MHz, τ_{80}, is equal to 1.3. This then predicts flux densities of 37 and 49 f.u. at 408 and 178 MHz respectively. The 408 MHz flux density fits this interpretation and the predicted 178 MHz flux density is equal to our estimate of the upper limit to the true value. However, we note that acceptance of a value near this limit would also be required if mechanisms (ii), (iii) or (iv) were responsible and thus an improved spectrum could be used only to distinguish between (i) and the other possibilities.

The path to 3C 391 is greater than 8.5 kpc and at very low galactic latitude. Holden and Caswell (1969) note a similar though less severe low-frequency cut-off in the spectrum of W49B (G43.3−0.2), a source which also shows pronounced H I absorption and is at an inferred distance of 10 to 14 kpc (Kazès and Nguyen-Quang-Rieu, 1970; Radhakrishnan *et al.*, in preparation), comparable with the distance of 3C 391.

For W49B, Holden and Caswell (1969) interpreted the low-frequency cut-off as free-free absorption in the intervening medium with an optical depth corresponding to $\tau_{80} = 0.45$. They suggested that such absorption could arise in either a hot diffuse ionized medium or a small hot cloud (H II region), but we note that the spectral data yield no information on the temperature of any intervening absorbing medium [Milne's (1969) calculation of its temperature is not valid] and cannot distinguish whether such a medium is diffuse or composed of dense clouds occupying only a small fraction of the line of sight. Current views on the interstellar medium (e.g. Field *et al.*, 1969) suggest that low-energy cosmic rays sufficiently ionize low-temperature (e.g. $50° \mathrm{K} < T < 150° \mathrm{K}$) H I clouds for them to cause effective free-free absorption of low-frequency continuum radiation. Since the H I absorption measurements indicate the existence of such clouds along the line of sight to both 3C 391 and W49, they could naturally explain the low-frequency continuum absorption too.

A model in which clouds at 50° K with electron densities of $n_e \approx 0.4\ \mathrm{cm}^{-3}$ fill only 1% of the line of sight would yield the required absorption for 3C 391. In contrast, a uniform medium at 10^4° K would require a mean electron density of $n_e \approx 1.4\ \mathrm{cm}^{-3}$ to account for the absorption. We feel that free-free absorption within low-temperature clouds offers the most plausible explanation of the spectral turnover.

Conclusion

The source 3C 391 is non-thermal and at a distance greater than or equal to 8.5 kpc. Its surface brightness and linear size at this distance are compatible with its being a fairly typical supernova remnant. Its spectrum exhibits a change of slope near 408 MHz which we believe is due to free-free absorption in the intervening medium, probably within partially ionized, low-temperature H I clouds. More accurate measurements of the spectrum between 80 and 408 MHz would indicate whether an alternative possibility, a low-energy cut-off in the electron energy spectrum within the source, can be definitely ruled out.

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