THE RADIO SOURCE 1934−63

By K. I. Kellermann*

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Summary

Observations of the radio source 1934−63 have been made at a large number of frequencies between 350 and 5000 Mc/s using the CSIRO 210 ft radio telescope. The spectrum is found to be broadly peaked near 1400 Mc/s. At higher frequencies, the spectral index is approximately $-1\cdot2$, while below 1400 Mc/s the flux density rapidly decreases with decreasing frequency. The form of the spectrum may be explained as synchrotron radiation from relativistic electrons having an energy distribution of the form $N(E) = KE^{-3\cdot4}$ and where there is either absorption due to free–free transitions in an ionized hydrogen region having an emission measure about 10^6 cm^{-6} pc, and an electron temperature of 10^4 °K, or self-absorption by the relativistic electrons. Assuming a magnetic field of 10^{-2} G, the angular size of the source must then be about $0''\cdot002$, the linear dimensions of the order of, or less than, 20 pc, the surface brightness about 5×10^{12} °K at 400 Mc/s, and the density of relativistic electrons about 10 cm^{-3}. A normal power-law spectrum can also be modified at low frequencies if the synchrotron emission occurs in a region where the index of refraction is less than unity. A density of 4×10^3 electrons/cm^3 is needed to produce the observed cut-off at 1400 Mc/s.

The possibility that the source may be an artificial transmission from an intelligent civilization is also discussed.

Measurements of the flux density below 200 Mc/s are needed to discriminate between the various models proposed to explain the spectral distribution.

I. Introduction

Several discrete radio sources are now known that exhibit a pronounced maximum in their flux density spectrum at decimetre wavelengths. The strongest of these is 1934−63, whose unusual spectrum was first noted during a routine survey of the southern sky at 20 cm (Bolton, Gardner, and Mackey 1963). Shklovsky (1965) has recently discussed this source and has shown that if the observed decrease in flux density below 1000 Mc/s is due to self-absorption then the source must be very small and probably quite young. The purpose of the present paper is to present the results of recent more detailed spectral observations and to discuss the possible physical nature of the source in terms of the new data.

(*a*) *Angular Dimensions*

There are no interferometric measurements of 1934−63. However, since the source is not resolved with a $7'\cdot5$ beam at 11 cm its angular size must be less than $1'\cdot5$ in both coordinates.

* Division of Radiophysics, CSIRO, University Grounds, Chippendale, N.S.W.; present address: National Radio Astronomy Observatory, Green Bank, West Virginia, U.S.A.

(b) *Optical Identification*

A plate taken by Minkowski with the 74 in. telescope at Mount Stromlo shows a galaxy and several stellar objects near the position of the radio source.* The galaxy, which has a visual magnitude of 18·4 (Bolton and Ekers, personal communication), has a bright starlike nucleus which appears to be joined to one of the stellar objects by a faint bridge (see Plate 1). The coordinates of the radio source are given below together with those of the galaxy and the star (Ekers, personal communication).

	α(1950)	δ(1950)
Radio source:	$19^{h}\,34^{m}\,48^{s}{\cdot}9$ ($\pm 2^{s}{\cdot}0$)	$-63°\,49'\,42''$ ($\pm 18''$)
Galaxy:	$19^{h}\,34^{m}\,48^{s}{\cdot}3$	$-63°\,49'\,37''$
Star:	$19^{h}\,34^{m}\,49^{s}{\cdot}8$	$-63°\,49'\,28''$

(c) *Polarization*

Davies and Gardner (personal communication) have reported no linear polarization greater than 1% in the observed radio emission at 620, 960, 1410, and 2650 Mc/s. In a separate investigation, Roberts and Komesaroff (personal communication) find no evidence of circular polarization greater than 4% at 960 Mc/s.

II. The Radio Spectrum

The spectrum of 1934—63 has been measured in considerable detail over the frequency range 350–5000 Mc/s. At 408, 620, 960, 1410, 2000, 2650, and 5000 Mc/s the observations were made with standard Dicke receivers in routine use with the 210 ft telescope.

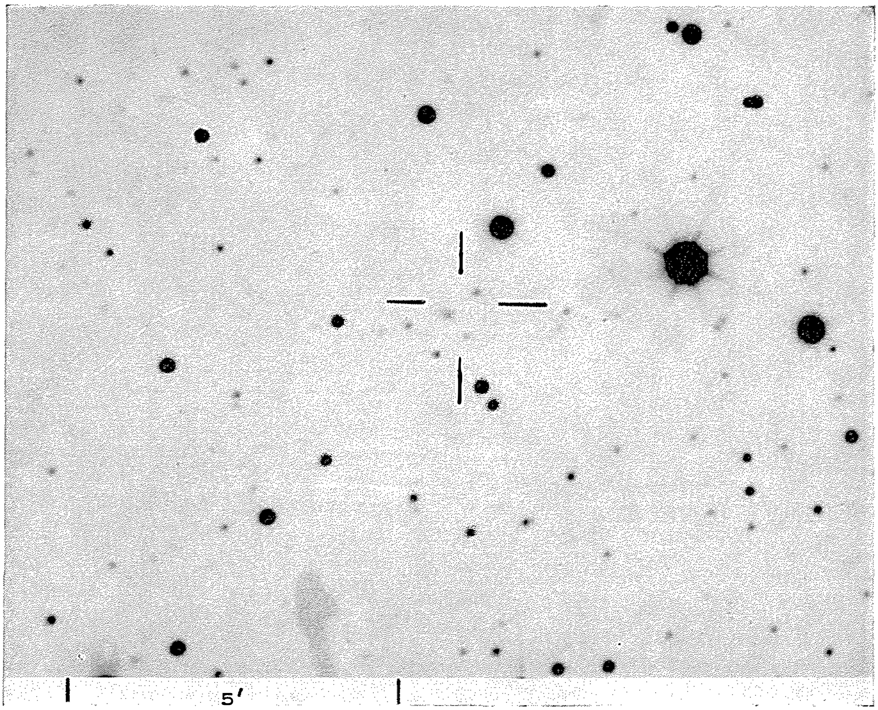
Between 350 and 1000 Mc/s, where the slope of the spectrum is changing rapidly, the flux was measured at a number of frequencies spaced only 20–25 Mc/s apart. These observations were made using available crystal mixer receivers and aerial feeds designed for nominal operation at 408, 620, and 960 Mc/s. The only modification introduced was to convert the receivers to total power systems, which permitted measurements to be made over the full bandwidth of the antenna feeds. The frequency was altered by merely changing the local oscillator frequency.

At each frequency, the flux density of 1934—63 was determined relative to the source MSH 19—4*6* (Mills, Slee, and Hill 1958). Previous observations had shown that, over the relevant range of frequencies, this source has a well-determined power-law spectrum, defined by a spectral index of $-0{\cdot}90$ and a flux density at 400 Mc/s of 39 flux units (1 flux unit (f.u.) = 10^{-26} W m^{-2} (c/s)$^{-1}$).

With the exception of the 5000 Mc/s measurement, the accuracy at frequencies above 1000 Mc/s is determined primarily by the accuracy of the flux density scale, which is thought to be correct to within about 5%. At 5000 Mc/s, the measured flux density has an uncertainty of about 10%. Below 1000 Mc/s, confusion becomes increasingly important, giving an uncertainty of about 1 f.u. at 350 Mc/s.

* The author is indebted to Dr. Minkowski for permission to reproduce this photograph.

RADIO SOURCE 1934−63



Optical field near the region of the radio source 1934−63. The solid lines indicate the position of the radio source.

III. Discussion

As shown in Figure 1, the radio spectrum of 1934−63 is broadly peaked near 1400 Mc/s and falls off rather rapidly above and below this frequency. These results differ from those of Bolton, Gardner, and Mackey (1963) in two main respects. First, the addition of a point at 5000 Mc/s clearly shows that the source is non-thermal,

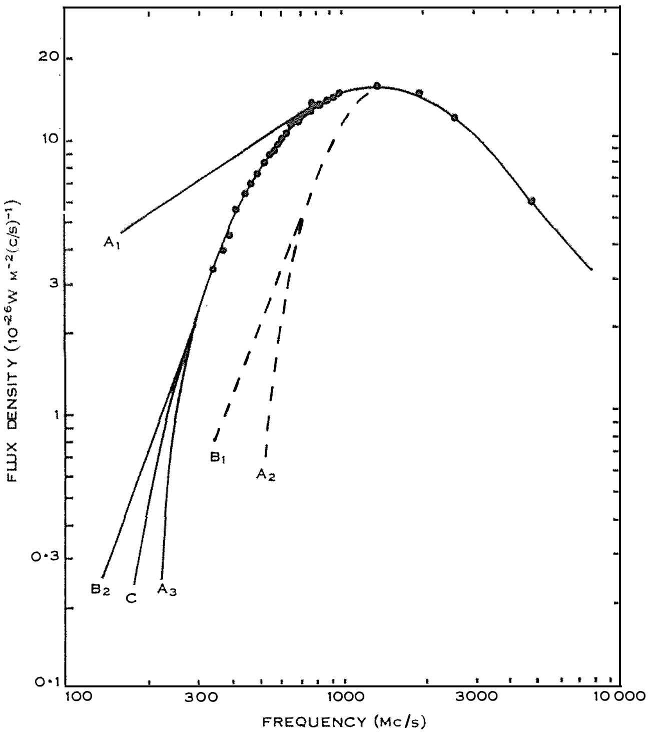


Fig. 1.—Theoretical and experimental spectrum for 1934−63. The measured flux densities at a number of frequencies are given (●) together with curves showing the spectra expected from the models discussed in the text. An electron energy distribution in the form $N(E) = KE^{-3\cdot 4}$ is assumed in each case. Curve A_1: ionized hydrogen uniformly mixed with the synchrotron radiation; curve A_2: ionized hydrogen with an emission measure $2\,T_e^{3/2}$ cm^{-6} pc located between the source and the observer; curve A_3: ionized hydrogen with an emission measure ranging from $\frac{1}{2}\,T_e^{3/2}$ to $8\,T_e^{3/2}$ cm^{-6} pc located between the source and the observer; curve B_1: self-absorption in a source with uniform brightness temperature $10^{15}\,B^{-\frac{1}{2}}$; curve B_2: self-absorption in a source where the brightness temperature varies across the source; curve C: synchrotron radiation in a medium where the density of thermal electrons is 4×10^{3} cm^{-3}.

although measurements at still higher frequencies are required to show whether the spectrum steepens further above this frequency; secondly, the new flux densities near 600 Mc/s are about 30% lower than the value given by Bolton, Gardner, and Mackey.

It is clear that the source of radio emission cannot be simple synchrotron radiation, since the power radiated by synchrotron emission never rises faster than (frequency)$^{\frac{1}{3}}$ for any distribution of electron energies. This follows from the radiation spectrum of a single electron, which is proportional to (frequency)$^{\frac{1}{3}}$ for frequencies well below the critical frequency.

Several mechanisms are known that can modify a normal synchrotron power-law spectrum to produce a sharp low energy cut-off of this type. These include synchrotron radiation where either (i) there is absorption due to free–free transitions of thermal electrons in ionized hydrogen, or (ii) there is self-absorption by the relativistic electrons, or (iii) the relativistic electrons are moving in a dispersive medium whose index of refraction is less than unity. The numerical values of the parameters required to fit the observed spectrum are discussed below for each of these processes.

(*a*) *Absorption in an Ionized Medium*

An initial power-law spectrum of synchrotron radiation will be modified at low frequencies by an ionized medium that has an absorption coefficient inversely proportional to the square of the frequency. Two cases may be considered, (1) where the synchrotron radiation originates within the absorbing medium, and (2) where the absorbing medium is located between the source and the observer.

Case 1

When ionized hydrogen is uniformly mixed with a source of synchrotron radiation having a power-law spectrum of the form $S = Af^{\alpha}$ (where α is the spectral index), the spectral dependence of the radiation observed at a point outside the medium is given by

$$S = \left(\frac{A}{f_0^2}f^{\alpha+2}+\frac{2\mathbf{k}}{c^2}\Omega f^2 T_{\mathrm{e}}\right)\left(1-\exp\{-(f_0/f)^2\}\right), \tag{1}$$

where Ω is the solid angle subtended by the source, T_{e} is the kinetic temperature of the ionized gas, f_0 is the frequency at which the optical depth is equal to unity, $\mathbf{k}$ is the Boltzmann constant, and c is the speed of light.

We will consider only the case where the thermal emission from the HII region is small compared with the non-thermal radiation reaching the observer, that is, where

$$\frac{2\mathbf{k}}{c^2}\Omega f^2 T_{\mathrm{e}} \ll \frac{A}{f_0^2}f^{\alpha+2}. \tag{2}$$

This assumption is justified in the case of 1934—63, where the steep high frequency spectrum and minimum observed flux density of 6 f.u. at 5000 Mc/s indicates that any thermal component must be less than a few flux units.

At sufficiently low frequencies, where $(f_0/f)^2 \gg 1$, the optical depth is large and equation (1) becomes

$$S = \frac{A}{f_0^2}f^{\alpha+2}. \tag{3}$$

If the non-thermal source in 1934—63 has a spectral index $\alpha = -1\cdot 2$, determined from the high frequency part of the spectrum, then at low frequencies where the

HII region is optically thick the index would be $\alpha' = \alpha+2 = +0\cdot8$. This is much less than the observed value as shown in curve A_1 of Figure 1, and we can therefore conclude that the spectrum of 1934−63 is not significantly altered by free–free absorption occurring within the source of synchrotron radiation.

Case 2

If the absorbing medium is located between the source and the observer, then we have

$$S = Af^{\alpha}\exp\{-(f_0/f)^2\}+\frac{2\mathbf{k}}{c^2}f^2T_e[1-\exp\{-(f_0/f)^2\}]\Omega. \tag{4}$$

Again, neglecting the second term, which represents the thermal emission from the ionized gas, equation (4) becomes

$$S = Af^{\alpha}\exp\{-(f_0/f)^2\}. \tag{5}$$

The frequency at which the optical depth is equal to unity is given approximately by

$$f_0^2 \sim 3\cdot6\times10^5\,T_e^{-3/2}\mathscr{E}\quad(\mathrm{Mc/s})^2, \tag{6}$$

where the emission measure $\mathscr{E}$ is given by

$$\mathscr{E} = \int n_e^2\,\mathrm{d}l, \tag{7}$$

with the electron density n_e in cm^{-3} and the thickness l in parsecs.

If the decrease in flux density observed below 1400 Mc/s in 1934−63 is due to absorption, then the optical depth is equal to unity at about 800 Mc/s. From equation (6), the necessary emission measure is approximately $2T_e^{3/2}$. If the absorption takes place in a region having a uniform emission measure of this value, the spectrum will have a much sharper break than is actually observed (curve A_2 in Fig. 1). Curve A_3, which gives a good fit to the observed spectrum, has been computed for a smooth variation of the emission measure across the absorbing region ranging from $\frac{1}{2}T_e^{3/2}$ to $8T_e^{3/2}$. The actual value of the emission measure derived in this way depends on the electron temperature, and therefore it cannot be determined uniquely unless the temperature and the corresponding ionization mechanism are known. The necessary values of the emission measure and the electron temperature do not, however, seem unreasonable. For instance, if T_e is of order 10^4 °K, then $\mathscr{E}$ has a value about $10^6\ \mathrm{cm}^{-6}$ pc. If the dimensions of the absorbing cloud are of the order of 1 kpc, then the required density of electrons is about $30\ \mathrm{cm}^{-3}$.

Greenstein and Schmidt (1964) have found that the strong emission lines in the quasi-stellar sources 3C 48 and 3C 273 must originate in regions having electron densities of about 3×10^4 and $3\times10^6\ \mathrm{cm}^{-3}$ respectively. They then conclude from the absence of any free–free absorption in the radio spectra of these sources that the radio emission originates outside the high density region. In contrast to this, the radio source 1934−63 may be located inside a dense shell of ionized hydrogen.

The absence of any linear polarization in the emission from 1934—63 is some evidence for a high density of thermal electrons, which, owing to the process of Faraday rotation, would depolarize any radiation from the source.

(b) *Self-absorption*

LeRoux (1961) and Twiss (1954) have shown that if the brightness temperature of a source approaches the equivalent temperature of the electrons, self-absorption will become important. More recently, the theory has been applied by Slish (1963) and Williams (1963) to observations of source spectra; they have shown that self-absorption may affect the low frequency spectrum of radio sources having a high surface brightness.

The flux density received from a gas of relativistic electrons with an energy distribution of the form $N(E) = KE^{\gamma}$, and having a volume emissivity ϵ and an absorption coefficient k, is given by LeRoux (1961) as

$$S = A\frac{\epsilon}{k}\{1-\exp(-kl)\}\theta^2, \tag{8}$$

where θ is the observed angular diameter and l is the depth of the source along the line-of-sight; kl represents the optical depth τ and can be written as

$$\tau = kl = \left(\frac{f}{f_0}\right)^{\frac{1}{2}(\gamma-4)}, \tag{9}$$

where f_0 is again the frequency where the optical depth is equal to unity. Equation (8) can then be written as

$$S = A'f^{2\cdot5}[1-\exp\{-(f/f_0)^{\frac{1}{2}(\gamma-4)}\}]\theta^2. \tag{10}$$

The exponent in the energy distribution, γ, is given by the usual expression $\gamma = 2\alpha-1$, where α is the spectral index at frequencies where τ is much less than unity. For 1934—63, $\alpha = -1\cdot2$ and $\gamma = -3\cdot4$. Equation (10) then becomes

$$S = A'f^{2\cdot5}[1-\exp\{-(f/f_0)^{-3\cdot7}\}]\theta^2. \tag{11}$$

Thus, for $f \ll f_0$, S is proportional to $f^{2\cdot5}$. The angular dimensions of the source may be estimated from the frequency at which the flux density reaches a maximum, $f_{\max}$, and the observed flux density $S_{\max}$ at that frequency (Slish 1963), as follows:

$$\theta = 9\cdot3\times10^{8}\, S_{\max}^{\frac{1}{2}}\, f_{\max}^{-5/4} B^{\frac{1}{4}}(1+z)^{\frac{1}{4}}, \tag{12}$$

where $S_{\max}$ is in flux units, B is the magnetic field strength in gauss, and z is the red shift.

As indicated below, the magnetic field strength is probably close to the equipartition value of 10^{-2} G. Using $f_{\max} = 1\cdot4\times10^9$ c/s, $S_{\max} = 15$ f.u., and assuming $B = 10^{-2}$ G and $z = 1$, we find the angular size θ is about $0''\cdot002$ and the corresponding surface brightness about 5×10^{12} °K at 400 Mc/s. As seen from equation (12), these values do not depend strongly on the assumed value for the magnetic field or the red shift. The expected spectrum of a source having a uniform brightness temperature of 5×10^{12} °K and a spectral index of $-1 \cdot 2$, calculated from equation (11) and shown in curve B_1 of Figure 1, is seen to have a sharper low frequency break than is observed. A broader peak would result if the brightness temperature varied across the source, thus causing a more gradual transition from small to large optical depth.

Although a variety of brightness distributions can be made to fit the observed spectrum, the simplest model that outlines the major features of the source has a magnetic field that ranges from 10^{-1} to 10^{-3} G, giving a total angular extent of the source of approximately $0'' \cdot 003$ but with half the observed radiation coming from a region only $0'' \cdot 0015$ in diameter. The corresponding spectral distribution is shown in curve B_2 of Figure 1 and is in good agreement with the observed flux densities over the range 350–5000 Mc/s.

Such a very small angular size would be significant in that cosmological theory predicts a limiting angular diameter for radio sources with very large red shifts (Hoyle 1959). In the steady-state universe, the angular size of an object with a "metric diameter" D will tend toward the asymptotic value $\theta = DH/c$ as the red shift z approaches infinity (H = Hubble constant). In all exploding universes characterized by a value of the deceleration parameter q_0 greater than zero, θ approaches a minimum value at red shifts of the order of unity and then increases as z is further increased. This minimum observed angular size is equal to DH/c and increases for increasing values of q_0. Thus, in any relativistic cosmology with q_0 greater than unity, D is less than, or of the order of, $c\theta/H$. With $q_0 = 1$ (Sandage 1961), the limiting dimensions become $(\frac{2}{3})^2(c\theta/H)$. Taking the Hubble constant as $H = 100$ km sec^{-1} Mpc^{-1} and $\theta \simeq 0'' \cdot 003$, we find for 1934−63 that

$$D \lesssim 45 \text{ pc for } q_0 = -1 \text{ (steady state);}$$
$$D \lesssim 20 \text{ pc for } q_0 = +1;$$
$$D \sim 45z \text{ pc for } z \ll 1 \text{ in any world model.}$$

If the object of approximately 18th magnitude near 1934−63 is identified with the radio source and is assumed to be a typical radio galaxy with $M_{\mathrm{pg}} \simeq -21$, then $z \simeq 0 \cdot 2$ and $D \simeq 9$ pc. If it is a quasi-stellar source with $M_{\mathrm{pg}} \simeq -25$, then $z \sim 1$ and $D \simeq 20$ pc. An alternative possibility is, of course, that it is optically non-luminous and relatively close, with D much less than 1 pc. In any case the dimensions cannot greatly exceed 20 pc, no matter how distant the source.

The total flux received from 1934−63 can be obtained by integrating the observed spectrum, and it is found to be approximately 5×10^{-16} W/m². The power L radiated by the source, if it has a red shift z, is then of order $6 \times 10^{44}\, z^2$ erg/sec. This is of the same order as the power radiated by the strong radio galaxies or quasi-stellar radio sources.

The energy contained in the magnetic field may be estimated from the relation

$$E_{\mathrm{m}} = \frac{1}{8\pi} \int B^2 \,\mathrm{d}V \sim 4 \times 10^{66} B^2 \theta^3 z^3 \sim 6 \times 10^{60} B^{11/4} z^3 \sim 10^{50} \text{ erg,} \tag{13}$$

while the energy of the relativistic electrons is given by

$$E_{\mathrm{e}} = \int N(E)E\,\mathrm{d}E = K\int E^{\gamma+1}\,\mathrm{d}E\,. \tag{14}$$

The well-known equation for the power radiated by electrons having an energy distribution of the form $N(E) = KE^{\gamma}$ (e.g. Woltjer 1958) can be written as

$$P(f) = 6\cdot85\times10^{-6}\,Kf^{\frac{1}{2}(\gamma+1)}\,B_{\perp}^{-\frac{1}{2}(\gamma-1)}\,F(\gamma), \tag{15}$$

where $F(\gamma)$ is of order $1\cdot8$ for $\gamma = -3\cdot4$. From equation (15), the value of K may be determined from the observed flux density at any frequency above 2000 Mc/s where the source is optically thin. The total electron energy E_{e} is then $10^{51}\,B^{-9/4}z^2$ erg if the lower cut-off of the electron energy distribution is taken as $0\cdot1$ GeV.

The total energy contained in the form of relativistic particles and in the magnetic field is then

$$E_{\mathrm{t}} \sim 10^{51}\,B^{-9/4}z^2+6\times10^{60}\,B^{11/4}z^3. \tag{16}$$

This is minimized when B is of order $10^{-2}\,z^{-1/5}$ G, corresponding to $E_{\mathrm{e}} \sim 3\times10^{55}\,z^{2\cdot45}$ erg. With the luminosity L of order $6\times10^{44}\,z^2$ erg/sec and z of order 1, the lifetime of the radio source cannot be more than 1000 years unless the supply of relativistic particles is continuously replenished. If the magnetic field is increased to 10^{-1} G, the decay time of the electrons due to radiation loss is only about 30 years. On the other hand, if the magnetic field is 10^{-3} G, the energy stored in the field is only about $4\times10^{52}\,z^3$ erg, which seems rather small compared with a radiation rate of $6\times10^{44}\,z^2$ erg/sec. Moreover, the energy of the relativistic particles would then be some 10^5 times greater than that stored in the magnetic field. Under these conditions the particles could not be contained, and the source would expand rapidly.

The density n_{e} of relativistic particles can be determined directly from the expression given by LeRoux (1961) for the absorption coefficient of a relativistic gas. For $\gamma = -3\cdot4$, the expression becomes

$$k = 1\cdot2\times10^{-12}\,B^{2\cdot7}f^{-3\cdot7}n_{\mathrm{e}}\quad \mathrm{m}^{-1}. \tag{17}$$

The optical depth $\tau = kl$ is equal to unity near 800 Mc/s. With $l = 20$ pc, $B = 10^{-2}$ G, and $f_0 = 8\times10^6$ c/s, n_{e} is of the order of 10 cm^{-3}. This may be compared with the relativistic particle density in strong radio galaxies of about 10^{-5} cm^{-3}, although Greenstein and Schmidt (1964) consider that in some quasi-stellar sources, such as 3C 273B, the particle density may be as high as 1 cm^{-3}. The required density is 5×10^3 cm^{-3} if $B = 10^{-3}$ G and $0\cdot02$ cm^{-3} if $B = 0\cdot1$ G.

The high density of relativistic particles and the small physical dimensions suggest that 1934—63 must be very young, perhaps a pre-quasi-stellar radio source as has been proposed by Shklovsky (1965). According to Shklovsky (1961*b*, 1965), the region containing the relativistic particles expands with a velocity close to that of light. The linear size of less than 20 pc deduced above then implies an age of less than 35 years. Shklovsky (1961*a*) has shown that if the magnetic flux is conserved during the expansion, the radio flux density S at frequencies where the optical depth is small, and also the frequency corresponding to maximum flux density, will both decrease with time according to the relations

$$\frac{\Delta S}{S} = 2(1-2\alpha)\frac{\Delta T}{T}, \qquad \frac{\Delta f_{\max}}{f_{\max}} = -\frac{5-4\alpha}{2\cdot 5-\alpha}\cdot\frac{\Delta T}{T},$$

giving $\Delta S/S \sim 20\%$ per year and $\Delta f_{\max} \sim -100$ Mc/s per year.

Even if the rate of expansion of the source is slowed down by the intergalactic medium (which Shklovsky considers unlikely) to a tenth of the velocity of light, the age is still only a few hundred years and the corresponding secular decrease in flux density and $f_{\max}$ still significant.

In order to check on any possible secular variations, the flux density of 1934−63 was remeasured at 2650 Mc/s relative to MSH 19−46 in January 1965 and compared with an earlier accurate measurement made in March 1964. The ratios obtained for the two measurements are

$$\text{January 1965:} \qquad \frac{S(1934-63)}{S(19-46)} = 1\cdot 708 \pm 0\cdot 025;$$

$$\text{March 1964:} \qquad \frac{S(1934-63)}{S(19-46)} = 1\cdot 725 \pm 0\cdot 026.$$

This indicates that any secular change at this frequency is less than a few per cent per year, implying an age of at least several hundred years.

Comparison of the flux densities measured during this program with the earlier spectrum of Bolton, Gardner, and Mackey (1963) shows a large discrepancy near 50 cm. Since it appeared that this might be due to a real change in the flux density, the original records, which were kindly made available to the author by J. G. Bolton, were re-examined to see if the apparent differences were significant. These earlier observations, which were made with simple receivers, were found to have a low signal-to-noise ratio and were subject to considerable uncertainties due to poor receiver stability and intermittent interference, and it appears that the present results are within the limits of error of the earlier work.

(c) *Effect of a Dispersive Medium*

If the relativistic electrons are moving in an ionized medium where the index of refraction is less than unity, the velocity of the electrons is less than the phase velocity of light in the medium. The radiation is then no longer concentrated along the electron trajectory as is the case for radiation from an extremely relativistic particle moving in a vacuum. Most of the emission is thus in the low order harmonics, rather than in the higher harmonics found for the usual synchrotron radiation in a vacuum. It follows that where the index of refraction varies with frequency, the low frequency spectrum of the radiated power will then differ from that in a vacuum.

The radio emission from ultra-relativistic electrons in dispersive media has been discussed in detail by Razin (1960). The power radiated by a single electron of energy E, as a function of frequency, is given by (Ginzburg and Syrovatskii 1964)

$$P(f) = \sqrt{3}\,\frac{e^3 B_\perp}{mc^2}\left\{1+(1-n^2)\left(\frac{E}{mc^2}\right)^2\right\}^{-\frac{1}{2}} \frac{f}{f_c'} \int_{f/f_c'}^{\infty} K_{5/3}(\eta)\,\mathrm{d}\eta \quad \text{erg/sec}, \tag{18}$$

where n is the index of refraction, given by

$$n^2 = 1-(f_m/f)^2, \tag{19}$$

and where

$$f_c' = f_c\left\{1+(1-n^2)\left(\frac{E}{mc^2}\right)^2\right\}^{-3/2}, \tag{20}$$

and f_c, the corresponding critical frequency in vacuum, is given by

$$f_c = 3\cdot 6\times 10^6\, B_\perp \left(\frac{E}{mc^2}\right)^2 \quad \text{c/s}, \tag{21}$$

and also

$$f_m^2 = 8\times 10^7\, n_e\,, \tag{22}$$

where n_e and B are in CGS units and e, m, and c are the usual atomic constants.

Equation (18) may then be written as

$$P(f) = \sqrt{3}\,\frac{eB}{mc^2}\left\{1+\left(\frac{f_m}{f}\right)\left(\frac{E}{mc^2}\right)^2\right\}^{-3/2} \frac{f}{f_c} \int_{f/f_c}^{\infty} K_{5/3}(\eta)\,\mathrm{d}\eta\,. \tag{23}$$

From equation (23) we see that the effect of the medium may be neglected when

$$\left(\frac{f_m}{f}\right)^2\left(\frac{E}{mc^2}\right)^2 \ll 1, \tag{24}$$

and from equations (21) and (22) this becomes

$$f \gg 20\,\frac{n_e}{B_\perp}. \tag{25}$$

Thus, for a field of 10^{-4} G the density of thermal electrons necessary to alter the spectrum below 1400 Mc/s is about 4×10^3 cm^{-3}. At this density, the rate of energy loss of the relativistic electrons due to ionization is about equal to the losses from synchrotron radiation, and the thermal bremsstrahlung losses are about 10 times greater. Absorption due to free–free transitions will also become important if the source size is greater than $0\cdot 1$ pc along the line-of-sight.

The spectrum expected from relativistic electrons having an initial energy distribution $N(E) = KE^{-3\cdot 4}$ in an ionized medium with an electron density of 4×10^3 cm^{-3}, and including the effects of electron energy losses, is shown in curve C of Figure 1.

(d) *Artificial Transmissions*

It is interesting to note that the spectrum of 1934−63 is remarkably similar to that predicted by Kardashev (1964) for signals transmitted by extraterrestrial "super civilizations". Kardashev suggests that in order to transmit the maximum rate of information, "cosmic intelligence" would be characterized by a spectrum which, like 1934−63, increases approximately as $(\text{frequency})^{2\cdot 7}$, reaching a maximum at decimetre or centimetre wavelengths and then falling off as $(\text{frequency})^{-1}$. The sources CTA 21 and CTA 102, which Kardashev has suggested might be artificial, have low frequency indices of about $+0\cdot 1$, while for 1934−63 the index is about $+2\cdot 5$.

Kardashev considers two cases, namely, a Type I civilization which is able to harness the power of its sun and transmit about 10^{27} W, and a Type II civilization which utilizes the entire radiated energy of a galaxy of 10^{37} W. The observed flux of 1934−63 of 10^{-16} W/m^2 then leads to distances of about 10 kpc and 3×10^3 Mpc for the Type I and Type II civilizations respectively. Assuming an absolute magnitude for a Type I civilization of +5 and of −20 for a Type II, the apparent photographic magnitude in both cases is about +20.

He also anticipates that there might be details in the spectrum near the 21 cm line to emphasize the artificial nature of the source. To check this possibility, J. Hindman and the author have investigated the spectrum of 1934—63 near 1400 Mc/s with a 48 channel receiver covering a $1\cdot 6$ Mc/s band with the hydrogen line. No unusual characteristics were found, but the range of frequencies investigated was limited, and it was not possible to draw any definite conclusions about the possible artificial nature of the source.

IV. Conclusions

The question of whether or not sources like 1934−63 represent the very early stages of quasi-stellar sources or radio galaxies is clearly an important one. As yet it is not clear whether normal galaxies, radio galaxies, quasi-stellar sources, and the recently discovered quasi-stellar galaxies (Sandage 1965) are genetically related or whether they are entirely different objects.

At the present time two other sources, CTD 93 (Kellermann and Read 1965) and Parkes 2127+04 (Day *et al.* 1966), are known that have pronounced maxima in their spectra. In addition, there are several sources, such as CTA 21 and CTA 102 (Kellermann 1964), with less well defined maxima, and at least two known sources, 3C 279 (Bolton 1963; Dent and Haddock 1965) and NGC 1275 (Heeschen 1961; Dent and Haddock 1965), that have normal spectra at metre and decimetre wavelengths but show a rapid increase in flux density at short wavelengths. Recent measurements made at 11 cm with the National Radio Astronomy Observatory interferometer (Clark and Hogg, personal communication) indicate that the high frequency emission in 3C 279 comes from a much smaller region than the metre wavelength source. It is likely that the high frequency radiations from 3C 279 and probably NGC 1275 as well derive from sources essentially separate from those giving the low frequency components and have spectra similar to 1934−63.

The sources 1934−63 and CTD 93 were first found from systematic surveys made at 21 cm and are inconspicuous at long wavelengths. It therefore seems reasonable that other similar sources may exist that have not been detected by the various metre and decimetre surveys currently in existence but which might be easily detectable by a systematic sky survey made at centimetre wavelengths. Obvious possibilities for such hypothetical centimetre sources are X-ray sources and the quasi-stellar galaxies, neither of which have been detected as radio sources at longer wavelengths.

Further radio and optical studies of these unusual sources are necessary to clarify their relation to other radio sources. Since 1934−63 is the strongest of these it has the best determined spectrum. But, unfortunately, because it is not visible from the major northern observatories, its spectrum cannot be extended beyond the frequency limits of the Parkes telescope. The possibility of other radio as well as optical work on this source is therefore limited.

With the information now available on 1934−63 it is not possible to determine uniquely the conditions responsible for the unusual radio spectrum. Modifications of a simple power-law spectrum by self absorption, free–free absorption, or the "Razin" effect can all be made to give a good fit to the observed spectrum, although each process requires some rather extreme properties. As pointed out by Menon (personal communication 1965), it is difficult to see how to maintain the large mass of ionized hydrogen apparently required to explain the low frequency cut-off due to free–free absorption or the Razin effect. Measurements of Hβ radiation and the ultraviolet continuum are needed before any detailed models can be pursued. The self-absorption model requires a rather large magnetic field of 10^{-2} G and an age of only a few hundred years. The sharp condensation seen near the centre of the brightest galaxy near the radio position suggests that a violent event has, in fact, recently occurred in the galaxy and supports Shklovsky's suggestion that 1934−63 is the early stage of a quasi-stellar source.

A clear distinction between these mechanisms can be made by extending the flux measurements to below 200 Mc/s, where the opacity is large and where the theoretical spectra begin to diverge (see Fig. 1). Such measurements might just be possible at 115 Mc/s with the new Mills Cross telescope, which is expected to have a sensitivity limit of 0·2 f.u. at this frequency (Mills *et al.* 1963).

A direct measurement of the angular size using very long baseline interferometry would test the reality of an angular size of $0''\cdot 002$ predicted by the self-absorption model. Resolutions of this order do not appear to be beyond the present state of the art, and such measurements are the only means of establishing directly the existence of radio sources with the dimensions and densities discussed in Section III.

Clearly it is also desirable to continue accurate measurements of the flux density over long periods to search for any possible secular or periodic variations in intensity.

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VI. References

Bolton, J. G. (1963).—Report at XIV General Assembly of URSI, Tokyo.

Bolton, J. G., Gardner, F. F., and Mackey, M. B. (1963).—*Nature* **199**: 682.

Day, G. A., Shimmins, A. J., Ekers, R. D., and Cole, D. J. (1966).—*Aust. J. Phys.* **19**: 35.

Dent, W. A., and Haddock, F. T. (1965).—*Nature* **205**: 48.

Ginzburg, V. L., and Syrovatskii, S. I. (1964).—"The Origin of Cosmic Rays." p. 75. (Macmillan: New York.)

Greenstein, J. L., and Schmidt, M. (1964).—*Astrophys. J.* **140**: 1.

Heeschen, D. S. (1961).—*Astrophys. J.* **133**: 322.

Hoyle, F. (1959).—Symp. IAU No. 9 (Paris 1958). p. 529.

Kardashev, N. S. (1964).—*Soviet Astr.* **8**: 217.

Kellermann, K. I. (1964).—*Astrophys. J.* **140**: 969.

Kellermann, K. I., and Read, R. B. (1965).—*Publs. Owens Valley Radio Observatory* **1**, No. 2.

LeRoux, E. (1961).—*Annls Astrophys.* **24**: 71.

Mills, B. Y., Aitchison, R. E., Little, A. G., and McAdam, W. B. (1963).—*Proc. Instn Radio Engrs Aust.* **24**: 156.

Mills, B. Y., Slee, O. B., and Hill, E. R. (1958).—*Aust. J. Phys.* **11**: 360.

Razin, V. A. (1960).—*Radiofizika* **3**: 921.

Sandage, A. R. (1961).—*Astrophys. J.* **133**: 355.

Sandage, A. R. (1965).—*Astrophys. J.* **141**: 1560.

Shklovsky, I. S. (1961*a*).—*Soviet Astr.* 4(2): 243.

Shklovsky, I. S. (1961*b*).—*Soviet Astr.* 4(6): 885.

Shklovsky, I. S. (1965).—*Nature* **206**: 176.

Slish, V. I. (1963).—*Nature* **199**: 682.

Twiss, R. Q. (1954).—*Phil. Mag.* **45**: 249.

Williams, P. J. S. (1963).—*Nature* **200**: 56.

Woltjer, L. (1958).—*Bull. Astr. Insts Neth.* **14**: 39.