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THE CENTRAL, COMPACT SOURCE IN THE CYGNUS A GALAXY

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ABSTRACT

Single, optically thin, component models as well as double, optically thick at low frequencies, component models have been examined in trying to explain the central source in the nucleus of Cygnus A. In the course of exploring those models, it is found that this compact radio source may be quite similar to other compact and variable sources in Seyfert galaxies and quasars. Double component models generally do better because they fit the X-rays, and there is a good chance that the X-rays arise in the central source; these models can naturally explain variability which may already have been detected in X-rays. The IR is most likely due to emission by cold dust in the nucleus of Cygnus A. Optical emission is, very likely, primarily thermal, except perhaps at UV wavelengths. A number of observations are suggested to check the predictions of this work.

Subject headings: galaxies: individual — galaxies: nuclei — radio sources: general

I. INTRODUCTION

Cygnus A has been studied since the early days of radio astronomy. It is one of the strongest radio sources in the sky and the strongest extragalactic source. The intense radio emission arises in two radio lobes that have been thoroughly studied. An inconspicuous—at radio wavelengths—compact radio source in the nucleus of the visible galaxy has been recently studied observationally (see Hobbs *et al.* 1978 for a summary of the observations). This source will be hereafter called the central source (in Cygnus A). It has a spectrum that is flat or rises above 1 GHz. At 300 GHz, if its spectrum remains the same, it would dominate the radio lobes. This work examines various models for this central source in Cygnus A and establishes the extreme importance of it in understanding the nature of Cygnus A.

In § II, observations relevant to the discussion are presented. In § III single, stationary cloud models are examined. In § IV, double compact cloud models are examined. In § V the variability of the central source is explored as well as its similarity to other compact, variable sources in Seyferts and quasars. Finally, in § VI, conclusions are drawn and future observations suggested.

II. OBSERVATIONS

The IR, optical, and, primarily, the radio observations were presented by Hobbs *et al.* (1978). Here, we discuss the observations—including the X-rays—relevant to the theoretical discussion of the present work.

The radio observations are summarized by Hobbs *et al.* (1978). Kellermann *et al.* (1975) found that the central source is very compact with a size of 0″.001 × 0″.002. Their single, elliptical Gaussian model may not be applicable, and the actual structure may be more complex than can be represented by any single-component model.

The total radio output of the two radio lobes is $\sim 1.7 \times 10^{45}$ ergs s^{-1} (cf. Hargrave and Ryle 1974), whereas the central source puts out $\sim 10^{44}$ ergs s^{-1} at radio frequencies below 100 GHz.

The IR luminosity in the 7.9–13.3 μm range is 3×10^{44} ergs s^{-1} (Rieke and Low 1972), whereas the total luminosity in the range 3500 Å to ~ 10 μm is probably close to a few times 10^{45} ergs s^{-1}.

The optical emission from Cygnus A is likely to be dominated by thermal processes and emission lines (Mitton and Mitton 1972). From the work of Sandage (1972) and van den Bergh (1976) the color indices are found to be $B - V = 0.95$ and $U - B = 0.35$, which are characteristic of starlight rather than nonthermal emission (cf. Matthews and Sandage 1963). In determining the optical flux densities from the U, B, V magnitudes the formulae of Matthews and Sandage (1963) were used.

The optical fluxes are fitted well with a blackbody curve at $T = 4000$ K. It is not clear whether nonthermal radiation makes a significant contribution to the optical fluxes. In view of the fact, though, that we are observing the nuclear region of a big cD galaxy, where starlight as well as line emission is important, we cannot say anything about a possible nonthermal component. The observed emission gives an upper limit to any nonthermal emission, and the observed optical emission could be entirely due to starlight (and/or emission lines).

The corrected visual magnitude, at a distance of 323 Mpc, corresponds to a visual luminosity of 8×10^{44} ergs s^{-1}.

The structure of the elliptical galaxy associated with Cygnus A has been discussed by van den Bergh (1976) and Kronberg, van den Bergh, and Button (1977). The galaxy consists of two distinct regions which are situated at opposite sides of the geometrical center of the cD envelope of the galaxy. This center coincides with the position of the compact radio source. It follows that the optical and radio observations do not necessarily correspond to the same region of the galaxy.

As Flasar (1971) points out, there are remarkable similarities between the lines of Cygnus A and the Seyfert galaxy NGC 1068. Flasar obtained temperatures in the range 15,000–20,000 K required to explain the line emission.

X-rays have been detected from the direction of Cygnus A. The observations are summarized in Culhane (1977). Longair and Willmore (1974) established an upper limit of 10′ for the size of the X-ray source and a total emission in the 0.6–7.5 keV range of 2.4×10^{45} ergs s^{-1}. Brinkman *et al.* (1977) find that if the source is associated with Cygnus A, it must be a source of greater than 12′ extent; or it could be a point source not associated with Cygnus A. Serlemitsos (1977) reported the detection of iron line emission from the source and tentative evidence to suggest that the X-ray source may be due to the hot gas in the Cygnus A cluster. Recently (Mushotzky and Serlemitsos 1978) the Goddard Space Flight Center (GSFC) group has detected variability in the X-rays from Cygnus A: In 1975 they observed a flux of 6.9×10^{-11} ergs cm^{-2} s^{-1} and in 1976 a flux of 4.4×10^{-11} ergs cm^{-2} s^{-1} in the 2–6 keV range (10% systematic errors); the corresponding flux observed by Longair and Willmore (1974) is 1.4×10^{-10} ergs cm^{-2} s^{-1}. The X-rays seen by the GSFC group could be fitted by a thermal gas of $kT = 6.5\,(+3.3, -1.9)$ keV or by a nonthermal spectrum of $\alpha = 1.15 \pm 0.4$. The X-rays seen by Longair and Willmore can be fitted either by a thermal spectrum of $kT \geq 5$ keV or by a nonthermal spectrum of $\alpha = 0.3$. The GSFC group have doubts as to the identification of the X-ray source with the cluster due to the observed variability, which amounts to about 50% over the period of a year.

The observed X-rays may arise in a hot intracluster gas rather than in a compact radio source within the nucleus of the galaxy. The following reasoning shows that this is unlikely: Assuming that $kT = 10$ keV and that the radius of the cluster is 1 Mpc, we find that the needed intracluster densities are $\sim 10^{-3}$ cm^{-3}. According to Culhane (1977) the X-ray core radii of clusters are, in most cases, a fraction of 1 Mpc. Moreover, the implied mass in hot intracluster gas would be 8×10^{13} $M_\odot$ ($R = 1$ Mpc); similar results hold for smaller sizes. This mass may be higher than the mass of all the galaxies in the Cygnus A cluster. The X-ray luminosity would imply, according to Bahcall (1977), a density of 35 galaxies per 0.5 Mpc radius of the cluster center, and this value would be higher than that of the Coma cluster. It may be that the Cygnus A cluster is one of the rich ones, both in galaxy membership and in hot gas abundance; but until such a claim is made in the literature, we regard the above values of density and mass as too high. Moreover, a hot intracluster gas could not explain the X-ray variability if indeed this is present.

Because of the problems associated with a cluster origin of the X-rays, we will assume that the X-ray emission comes from the nucleus.

The observations with their associated uncertainties are summarized in Figure 1. The radio points are discussed by Hobbs *et al.* (1978). The 10 μm observation is from Rieke and Low (1972). The optical (U, B, V) fluxes are from Sandage (1972) and van den Bergh (1976). Finally, the X-rays are drawn as observed by Longair and Willmore (1974). The GSFC data would give a flux less by about a factor of 2 and with a steeper spectrum.

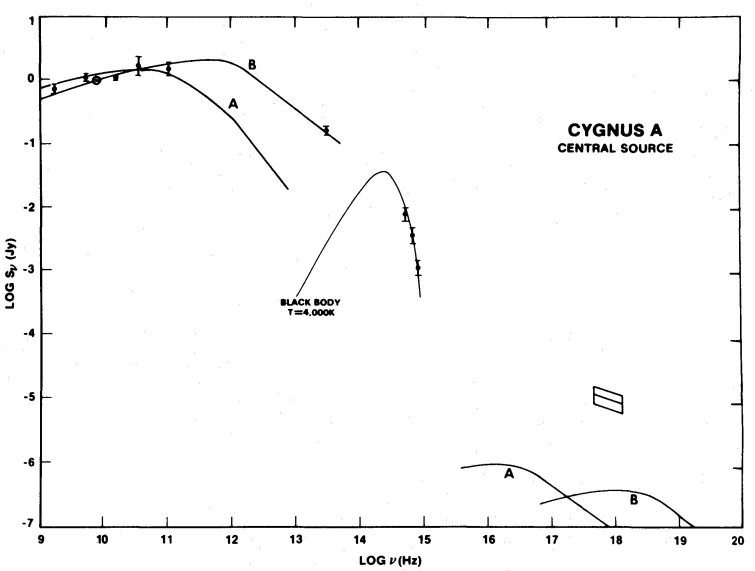

FIG. 1.—The electromagnetic spectrum of the central source in Cygnus A. Data are from Hobbs *et al.* (1978). Models A and B are shown. All these models are for single, optically thin, stationary clouds in the central source. A blackbody fit to the optical fluxes is also shown.

III. SINGLE, STATIONARY CLOUD MODELS

a) *Procedure*

From Figure 1 we note that the available observations at radio wavelengths indicate that the spectrum is rising or is at least constant below 100 GHz. Even at 99 GHz the spectrum has not yet turned over. In this section, we try to fit the radio data with a single, optically thin radio cloud, inside which isotropic distributions of magnetic field and electrons exist. Other workers in the field attempt to fit flat or slowly rising radio spectra with multiple component models. However, the spectrum below 100 GHz can be fitted with a $\frac{1}{3}$ power law ($S_\nu \propto \nu^{1/3}$). It is well known (Pacholczyk 1970) that a $\frac{1}{3}$ rise in the synchrotron spectrum comes about from the radiation of an assembly of relativistic electrons with a low-energy cutoff in their energy spectrum. The frequency dependence $\nu^{1/3}$ of the photon spectrum is the sharpest low-frequency cutoff that can be obtained in a "pure" synchrotron spectrum, unmodified by absorption or other processes (Moffet 1975).

We assume that the radio cloud is fed at its center by an unknown source, which could be a massive black hole or a spinar (Cavaliere, Morrison, and Pacini 1970). The electrons move through the magnetic field and through the photons which arise from their synchrotron process; the electrons lose energy via the synchrotron and synchrotron self-Compton processes. This latter process (cf. Jones, O'Dell, and Stein 1974*a*) occurs when the electrons scatter off the ambient photon field which happens to be the synchrotron emission of these, same, relativistic electrons.

A fit to the radio points with the $\nu^{1/3}$ law was performed. At high frequencies, greater than 100 GHz, the spectrum will eventually turn over and then follow a $\nu^{-\alpha}$ law, where $\alpha = (\gamma - 1)/2$. At low frequencies, less than 1 GHz, the spectrum will eventually steepen to $\nu^{5/2}$ due to the synchrotron self-absorption mechanism.

The electron distribution is given by

$$N(E)dE = N_0 E^{-\gamma} dE\,. \tag{1}$$

The high-frequency part of the spectrum may or may not be fitted to the 10 μm observation.

One may obtain the strength of the magnetic field in the radio cloud, the number density of the relativistic electrons, and the minimum energy of the electron spectrum through the following three relations:

1. From the minimum frequency ν_1 of the power law $\nu^{-\alpha}$ in the photon spectrum, the magnetic field H is related to the energy E_1 corresponding to this frequency. This frequency is at least 100 GHz, and E_1 is identical to the minimum energy in the electron spectrum. We have the relation

$$HE_1^2 = 6.25 \times 10^{-14} \nu_1 / y_1\,, \tag{2}$$

where H is the magnetic field in gauss, E_1 is the electron energy in GeV, ν_1 is the frequency in Hz, and y_1 is a parameter tabulated in Ginzburg and Syrovatskii (1964) having values between 1.8 and 4 for γ between 2 and 5. A similar relation can be found in other references (cf. van der Laan and Perola 1969).

2. From the inferred flux density S_ν at frequencies ν greater than ν_1,

$$S_\nu = 1.35 \times 10^{-25} a N_0 l H^{(\gamma+1)/2} \Omega \left(\frac{6.26 \times 10^{18}}{\nu}\right)^\alpha \tag{3}$$

where S_ν is the flux density in W m^{-2} Hz^{-1}, l is the extent of the radio cloud in cm, N_0 is the constant in equation (1), Ω is the solid angle of the source, and a is a parameter tabulated in Ginzburg and Syrovatskii (1964) having values between 0.103 and 0.0922 for γ between 2 and 5. A similar relation could have been found by fitting in the $\nu^{1/3}$ part (cf. Pacholczyk 1970).

3. Assuming that approximate equipartition between the electron gas and the magnetic field energies holds (condition for which the total energy involved is minimum), the following relation is obtained:

$$H^2 = 6\pi N_0 \frac{1}{2-\gamma} (E_2^{2-\gamma} - E_1^{2-\gamma}) \quad (\gamma \neq 2)$$

or (4)

$$H^2 = 6\pi N_0 \ln (E_2/E_1) \qquad (\gamma = 2)\,,$$

where E_2 is the upper energy in the electron spectrum. If there is steepening of the electron spectrum, then equation (4) is modified accordingly. In the above equations (2) and (3) an isotropic distribution of pitch angles is assumed; i.e., $\langle \sin \chi \rangle = \pi/4$ and $\langle \sin^2 \chi \rangle = \frac{2}{3}$ (cf. Felten and Morrison 1966; Flasar and Morrison 1976).

The system of equations (2)–(4) can be solved for E_1, H, and N_0. The flux density S_ν and the corresponding frequency ν are found from the particular fits for an assumed value of γ; ν_1 is also found from the fit since it is the minimum frequency at which the power law $\nu^{-\alpha}$ becomes applicable. The third equation of the system, (4), involves the ratio of the maximum and minimum energies of the electron spectrum E_2/E_1. This value can be estimated for the models that fit the IR point. If there is no need to fit this point, then a ratio has to be assumed and this ratio should yield self-consistent results for the model. In any event, the results do not depend very strongly on the ratio E_2/E_1 for values of γ equal to or higher than 2.5. This ratio is of the order of 10 for the models examined.

The results of the three equations depend on the size of the radio cloud. This was taken from the VLBI observations of Kellermann *et al.* (1975). We assumed here an angular diameter θ of 0".0016 which at the distance D of the source of 323 Mpc ($H = 50$ km s^{-1} Mpc^{-1}) corresponds to an angular diameter of 2.5 pc. For other values of θ, the derived parameters can be computed as indicated in Appendix A.

Once the values of E_1, H, and N_0 are determined by the above procedure, one may obtain the other physical parameters of the radio cloud, as shown in Appendix B.

The electrons are assumed to be streaming outward from the center of the radio cloud, where, presumably, their source is located. This source could be a very compact object. As the electrons are streaming out, though, they are expected to be losing energy because they are radiating via the synchrotron and the synchrotron self-Compton processes. The synchrotron spectrum is, therefore, expected to steepen near the frequency ν_b, where ν_b is found from (cf. Flasar and Morrison 1976; van der Laan and Perola 1969)

$$\nu_b(\mathrm{GHz}) = \frac{2.3H}{(H^2 + 8\pi U_{\mathrm{ph}})^2 t_d^2(\mathrm{yr})}, \tag{5}$$

where t_d is the time that it takes the electrons to diffuse out to a distance R from the center. A lower limit to the diffusion time of electrons from the radio cloud is found by assuming that they stream out at the speed of light (see the relevant discussion in Flasar and Morrison 1976). For a diameter of 2.5 pc, t_d is about 4 yr under this assumption. For self-consistency of the model, ν_b should be greater than ν_1, the minimum frequency of the power law $S_\nu \propto \nu^{-\alpha}$.

b) *Results*

A number of models were computed. We can distinguish two classes: those that fit the IR observations of Rieke and Low (1972), and those that only fit the radio points. The results are shown in Table 1 for two typical models. E^{SC} is the ratio of the total power radiated by the inverse-Compton scattering to the power radiated by the synchrotron process. The last entry in the table indicates whether the IR observation is fitted or not.

Both models shown have an electron exponent $\gamma = 2.5$. Models with different γ's were computed with similar results.

Model A fits the radio data. The total energy radiated by the central source is about 10^{44} ergs s^{-1}, an order of magnitude less than the total radio luminosity of the radio lobes. The synchrotron and Compton lifetimes of

TABLE 1

SINGLE, COMPACT RADIO CLOUD MODELS*

Parameter	Model A	Model B
γ	2.5	2.5
θ† (arcsec)	1.6×10^{-3}	1.6×10^{-3}
H (gauss)	3.85×10^{-2}	6.1×10^{-2}
E_1 (GeV)	0.33	0.84
n_e (cm^{-3})	6.7×10^{-2}	6.2×10^{-2}
L_S (ergs s^{-1})	9.6×10^{43}	1.7×10^{45}
U_{ph} (ergs cm^{-3})	3.85×10^{-5}	6.8×10^{-4}
t_S (yr)	26	4.2
t_C (yr)	38	0.9
t_d (yr)	4.1	4.1
E^{SC}	0.65	4.5
IR fitted	No	Yes‡

* In all these models the cloud is optically thin above 1 GHz to its own synchrotron radiation; the observed rise is then due to the existence of a low-energy cutoff in the electron spectrum.

† This value is the VLBI maximum size.

‡ Model B is not self-consistent, unless the electrons are produced and radiate *in situ*; or, as they stream out, they do not lose energy because they are being continuously accelerated.

NOTE.—γ is the exponent of the electron spectrum; θ is the angular diameter; H is the magnetic field; E_1 is the low-energy cutoff of the electron spectrum; n_e is the total electron density of the relativistic electron gas; L_S is the total synchrotron power; U_{ph} is the energy density of the photon gas; t_S is the synchrotron lifetime of electrons of energy E_1; t_C is the corresponding inverse-Compton lifetime; t_d is the minimum diffusion time for electrons streaming out from the center (at the speed of light); and E^{SC} is the ratio of emissivities integrated over all frequencies.

electrons of the minimum energy in the electron spectrum E_1 are tens of years, longer than the minimum diffusion time. This model is therefore self-consistent; the photon spectrum would break at $\sim 10^{12}$ Hz and then follow a power law of $\nu^{-(\alpha+1/2)}$ if there is continuous injection (Kardashev 1962). The radio power increases from 1 GHz to 100 GHz and then turns over above this frequency.

Model B fits the IR point, as well as the radio points. The total power radiated in the radio would be comparable to that of the radio lobes; in fact, the total power radiated over all frequencies would be more than the radio luminosity of the lobes, because model B would have an appreciable total X-ray power due to the self-Compton process. Due primarily to the strong self-Compton emission, the electrons would lose their energy before they had time to travel an appreciable path starting from the center. This model is therefore viable only if the electrons are radiating their energy close to where they are being injected (*in situ* production of relativistic electrons). Such a situation may be expected to hold if the compact source in Cygnus A is a spinar (cf. Flasar and Morrison 1976, for spinars in the radio lobes of Cygnus A). Alternatively, models that fit the IR are viable if there is continuous acceleration of the electrons, so that they may escape from the cloud without losing their energy.

Using the formulae found in Dent and Haddock (1965), the frequency at which the optical depth of the cloud to its synchrotron radiation becomes equal to 1, is about 2×10^9 Hz for all models. The fits with a power law of the form $\nu^{1/3}$ are therefore self-consistent. It would be important to observe the compact source in Cygnus A at frequencies below 1 GHz to see whether the spectrum steepens.

Models A and B are shown in Figure 1.

The optical points could also be fitted by the extension of model B if this extension represents the exponential dropoff present at high frequencies due to the high-energy cutoff of the electron spectrum. However, it is more likely that the optical fluxes are dominated by thermal processes and emission lines, and the shown blackbody fit may be more appropriate.

The 10 μm observation is far above any hot (several thousand degrees) blackbody curve. If it is nonthermal and the size of the source is the VLBI size, then *in situ* production or continuous acceleration is required for the relativistic electrons. The situation does not change even if one invokes more than one radio cloud (see discussion in § IV). This phenomenon also applies to other extragalactic infrared and optical sources. However, in view of the domination of the optical emission in Cygnus A by thermal processes and emission lines, it is tempting to invoke (thermal) emission from cold dust for the IR.

Ptak and Stoner (1977) explain the IR observations in Seyfert galaxies as due to emission by dust at ~ 100 K. The 2–1000 μm spectra of M82 and NGC 253 indicate emission by cold, $T \sim 40$ K, dust (Elias *et al.* 1978). Finally, Mushotzky *et al.* (1978) interpret the 2–12 μm data from Cen A as also explained by emission from cold dust. If the IR is explained as emission from cold dust in the case of Cygnus A, then one would expect lack of variability in the infrared (see also § V). Polarization measurements in the IR of the type conducted for Seyfert galaxies and quasi-stellar sources (Kemp *et al.* 1977) could give some insight as to the nature of the IR emission process.

On the other hand, the high temperatures required for the [O II] line emission, and the short cooling time scale that follows (Kafatos 1973), require the presence of an energy source to maintain the high-excitation state of the line emitting region; such a source could indeed be the compact radio source at the center, as long as it has a power output of ionizing photons and high-energy particles in excess of, say, 5×10^{44} ergs s^{-1}. Mitton and Mitton (1972) also concluded that the hot gas in the nuclear region requires a continuing source of energy.

Assuming that the X-rays are from the galaxy itself, they cannot be accounted for by direct synchrotron radiation. They could arise from the inverse-Compton scattering of the synchrotron photons by the relativistic electrons. We have computed the self-Compton spectra by using the formulae found in Jones, O'Dell, and Stein (1974*a*) in the region of the spectrum with power exponent $-\alpha$. The self-Compton power is spread over a much wider frequency range than the corresponding synchrotron emission, but it essentially follows the same power laws. The calculated X-ray spectra are shown in Figure 1.

None of the models can explain the observed X-rays; model B gives a flux density less by a factor of at least 5 (for the GSFC results), or a factor of at least 10 (for the results of Longair and Willmore). Better results would be obtained for models that have turnover frequencies beyond that of model A but not as high as that of model B; however, such models could not account for the IR observations; moreover, such models, like B, would require *in situ* production or continuous acceleration of high-energy electrons.

Inverse-Compton scattering off the background photons or the starlight photons would be negligible in all cases.

The only way to reconcile the X-rays with emission by a single compact cloud is to assume that they arise in a hot, thermal—and compact—cloud in the nucleus of Cygnus A. This cloud would coexist with the radio cloud. Taking $kT = 10$ keV, consistent with the X-ray observations, we find the number density of the thermal electrons to be $\sim 6 \times 10^5$ cm^{-3} and the associated mass of the hot gas $\sim 10^5\ M_\odot$ (all this for the VLBI size). Such a hot, thermal, gas will cause a free-free absorption of the synchrotron spectrum (Allen 1968) below 1 GHz. The total power radiated by bremsstrahlung would be $\sim 2.5 \times 10^{45}$ ergs s^{-1}. The synchrotron radiation would be completely depolarized as it goes through the hot gas component of the radio cloud (cf. Moffet 1975; Wardle 1971).

If there is such hot gas of the densities derived above, it may be rapidly expanding because of its high gas pressure; on the other hand, a central mass $\sim 10^9\ M_\odot$ could certainly confine the hot gas (cf. Katz 1976; Schnopper *et al.* 1977).

Katz (1976) has suggested that nonrelativistic Compton scattering of a source of soft photons by a hot gas cloud could explain the optical (power law) spectra in quasars. Schnopper *et al.* (1977) considered this mechanism in the case of the Seyfert galaxy 3C 120. A power law of this kind could not explain the steep spectrum of Cygnus A at optical wavelengths, but could, say, produce an appreciable fraction of the observed total flux in the near-UV.

In this section, single stationary cloud models were examined. These models have the advantage that the parameters of the radio cloud can be determined with few assumptions.

Other workers have considered optically thin emission for sources with flat spectra (e.g., Altschuler and Wardle 1977; Marscher 1977). They, however, do not assume the presence of a low-energy cutoff in the electron spectrum which would result in a $\nu^{1/3}$ law for the synchrotron spectrum. The assumption $\gamma = 1$ then has to be made in order to fit a flat spectrum, and the problems associated with it are too great (cf. Marscher 1977). Jones, O'Dell, and Stein (1974*b*) briefly considered the possibility that the $\nu^{1/3}$ law applies in compact nonthermal sources. They, however, dismiss it for the majority of the sources because the observed spectra are appreciably steeper than this law. It is, of course, possible that a law of this kind applies to a source with a considerably flat spectrum, such as the compact source in Cygnus A.

In the case of Cygnus A it is found that such single cloud models and the associated, required, $\frac{1}{3}$ rise in the synchrotron spectrum are viable in fitting the radio data. They, however, fail to explain the X-rays (assuming, of course, that the X-rays come from the galaxy itself) unless more assumptions are introduced (such as *in situ* production of electrons). In order to fit the X-rays with a single cloud model, a hot cloud coexisting with the radio cloud has to be postulated.

IV. DOUBLE, COMPACT CLOUD MODELS

In § III we examined single cloud models. Hachenberg *et al.* (1976) used a single cloud to fit their 35 GHz observation of Cygnus A.

Double component models are normally used to fit the flat—or slowly rising—spectra of variable radio sources. The compact component accounts for the variability, whereas the extended component with falling spectral flux density is considered stationary (cf. van der Laan 1966).

For Cygnus A, both components are found to be small in size: The more extended one, hereafter referred to as component I, is found to be about half the maximum size allowed by the VLBI observations whereas the more compact cloud, hereafter referred to as component II, is an order of magnitude smaller than component I. The radio points are fitted with the two components, both of them being optically thick below some correspondingly different frequency and optically thin above it.

The great advantage of using double component models for the central source in Cygnus A is that the X-rays can be naturally interpreted as self-Compton radiation (from component II) and at the same time good fits to the radio can be obtained. The price one has to pay, though, is that these radio fits are not unique in the sense that the turnover frequencies of each component and the electron spectrum exponent γ are not fixed by the observations. The sizes—and cloud parameters—are therefore not uniquely determined. Another justification for the procedure followed here is that Kellermann *et al.* (1975) found that their single elliptical Gaussian model of the central source does not give a particularly good fit to the data and the actual structure is apparently more complex than can be represented by any single-component model. A double, or multiple, component model for the central source also agrees with the nondetection of the source at 2.3 GHz (Gubbay *et al.* 1977).

Fits of the radio observations were obtained with two compact clouds of an electron spectrum exponent $\gamma = 2$. The first radio cloud, component I, has a turnover frequency (from optically thin to optically thick regions of the spectrum) $\nu_A = 3$ GHz and a corresponding flux density of $S_{\nu_A} = 1.3$ Jy. The second cloud, component II, has a turnover frequency $\nu_A = 35$ GHz and a corresponding flux density $S_{\nu_A} = 1.7$ Jy. Next, the formulae of Jones, O'Dell, and Stein (1974*b*) were utilized to obtain the visible angular radius and the magnetic field inside each of the clouds, from the flux densities and frequencies in the optically thin and thick regions of the spectrum:

$$\frac{\theta}{2}(\text{ms}) \approx 0.427 \times 4.49^{[2(2\alpha-1)]/(3+2\alpha)} \times \left\{\left[\frac{1}{i_{\alpha_0}}\left(\frac{S_{\nu_A}}{\text{Jy}}\right)\left(\frac{\nu_A}{\text{GHz}}\right)^{-5/2}\right]^{1+\alpha}\left[e_{\alpha_0}{}^{\text{SC}} \log \Lambda\left(\frac{E_\nu{}^{\text{SC}}}{100\%}\right)^{-1}\left(\frac{S_{\nu'}}{\text{Jy}}\right)\left(\frac{\nu'}{\text{GHz}}\right)^{\alpha}\right]^{1/2}\right\}^{1/(3+2\alpha)}$$

and

$$H(\text{mG}) \approx \frac{2.15(408)^{2(2\alpha-1)/(3+2\alpha)}}{\sin\chi} \times \left\{\left[e_{\alpha_0}{}^{\text{SC}} \log \Lambda\left(\frac{E_\nu{}^{\text{SC}}}{100\%}\right)\left(\frac{S_{\nu'}}{\text{Jy}}\right)\left(\frac{\nu'}{\text{GHz}}\right)^{\alpha}\right]\left[\frac{1}{i_{\alpha_0}}\left(\frac{S_{\nu_A}}{\text{Jy}}\right)\left(\frac{\nu_A}{\text{GHz}}\right)^{-5/2}\right]^{-1}\right\}^{2/(3+2\alpha)}, \quad (6)$$

where we assume $\alpha = 0.5$. In the above formulae, the parameters i_{α_0} and $e_{\alpha_0}{}^{\text{SC}}$ are tabulated in Jones, O'Dell, and Stein (1974*a*). It was assumed that $\log \Lambda = 1$; $S_{\nu'}$ and ν' are the flux density and the corresponding frequency in the optically thin region of the spectrum; χ is a typical pitch angle and again an isotropic distribution of pitch angles was assumed. The quantity E_ν^{SC} is the ratio of spectral emissivities of self-Compton radiation to synchrotron radiation and is related to E^{SC}, the ratio of emissivities—integrated over all frequencies—as shown in Jones, O'Dell, and Stein (1974*a*) by

$$E^{SC} \approx (1.7)^{1-\alpha} \frac{\nu_b^{1-\alpha} - \nu_A^{1-\alpha}}{(1-\alpha)\nu_H^{1-\alpha}} E_\nu^{SC} . \tag{7}$$

In equation (7), ν_A is the lowest frequency for which the power law $S_\nu \propto \nu^{-\alpha}$ is applicable (the turnover frequency), ν_b is the upper frequency for which this power law is applicable (corresponding to the break-frequency of eq. [5]), and ν_H is the cyclotron frequency, $\nu_H = 2.8 \times 10^6 H$(Hz).

The results of this procedure are shown in Table 2. The last entry of this table gives the assumed, flux density at 10^{18} Hz (in Jy).

Component I contributes negligibly to the observed X-ray fluxes; we find that if $E_\nu^{SC} > 1/800$, then the computed E^{SC} is unreasonably high. The shown model, therefore, is for the minimum angular radius allowed (and the minimum magnetic field). If E_ν^{SC} is even less than 1/800, then the size and magnetic field can become larger. However, the maximum allowable radius is 8×10^{-4} arcsec, which is fixed by the VLBI estimates; the corresponding magnetic field is 0.19 gauss, and the computed flux at 10^{18} Hz is only 10^{-9} Jy in this case. Component I has computed parameters not too different from those of single, optically thin clouds.

Component II contributes 100% to the observed X-rays (5×10^{-6} Jy at 10^{18} Hz, where we have assumed the value of the X-ray flux seen by the GSFC group). The spectrum would steepen around 15 keV, and therefore it would be important to extend the present X-ray observations to slightly higher energies. The radio spectrum would steepen around 3×10^{11} Hz, and therefore it cannot account for the 10 μm observations. Both components do not contribute more than one-tenth of the observed IR, unless *in situ* production is postulated. These double compact cloud models therefore have the same difficulties encountered by the single, optically thin cloud models in fitting the IR. Emission by cold dust may well be required. If dust, heated by trapped Lα line radiation, is the source of IR radiation (Ptak and Stoner 1977), then $\sim 3\ M_\odot$ of dust is required to explain the IR, a very reasonable amount.

We note that the X-rays from Cen A were accounted for by the self-Compton model (Mushotzky *et al.* 1978) in a procedure similar to that done above. The IR from Cen A was explained by Mushotzky *et al.* as coming from cold (25–40 K) dust; it is interesting to note that Cen A has a lot of dust and gas, highly unusual for an elliptical galaxy, and it seems in this respect to be similar to Cygnus A, which apparently also contains dust and gas.

The general result that the smaller, optically thick cloud has higher fields than the larger—but still optically thick at low frequencies—cloud, does not depend on the specifics of the particular model presented here. Moreover, the X-rays must be coming from the smaller cloud and this is another general result. Another model was computed for $\alpha = 1$ but the same turnover frequencies ν_A with similar results.

We did not consider here small pitch angles because they are unrealistic (Jones, O'Dell, and Stein 1974*b*).

TABLE 2

Two Compact Radio Clouds in the Central Source of Cygnus A*

Parameter	Component I	Component II
Angular radius (arcsec)	3.8×10^{-4}	3.8×10^{-5}
H (gauss)	1.9×10^{-2}	0.25
ν_A (GHz)	3	35
ν_b (GHz)	3×10^3	3×10^2
$h\nu_b{}^X$ (keV)	2×10^4	15
L_S (ergs s^{-1})	3.5×10^{43}	4.5×10^{43}
t_S (yr)	420	3
t_C (yr)	90	0.9
t_d (yr)	1.9	0.2
S_ν (10^{18} Hz) (Jy)	10^{-7}	5×10^{-6}

* Here it is assumed that the exponent of the photon spectrum, α, is 0.5; similar results were obtained for $\alpha = 1$.

Note.—H is the magnetic field; ν_A is the transition frequency from optically thick to optically thin spectrum; ν_b is the upper break frequency of the radio spectrum; $h\nu_b{}^X$ is the corresponding energy of the photons at X-rays; L_S is the synchrotron power; t_S is the synchrotron lifetime of electrons radiating at frequency ν_A; t_C is the corresponding inverse-Compton lifetime; t_d is the minimum diffusion time for electrons; S_ν is the assumed flux density at the indicated frequency (component II accounts for practically all the X-rays).

V. COMPARISON OF CYGNUS A WITH OTHER COMPACT, VARIABLE, RADIO SOURCES

The compact source in the center of Cygnus A, unlike nuclei of Seyfert galaxies and quasars, has not been considered up to now to be a variable source. This may be due to reasons other than nonvariability of this source. There is only one measurement at IR wavelengths; and the optical, as we saw, is likely to be dominated by thermal processes. Radio measurements are hard to make, due to the dominance of the radio lobes; therefore, a single observation has been at each indicated radio frequency. In the only case where two observations were made at the same frequencies (X-rays) variability in a time scale of a year was indicated (Mushotzky and Serlemitsos 1978).

On the basis of the previous section and the similarities of the compact source in Cygnus A with other compact, and variable, radio sources (see discussion below), one strongly suspects that this source should also be variable.

The radio measurements were made between the beginning of 1973 and the beginning of 1977. Since the maximum value of the flux at GHz frequencies is about a factor of 3 greater than the minimum flux, we cannot say anything more than that the radio data indicate that any variability cannot exceed a factor of 3 over the period of 4 years. On the other hand, the X-ray data indicate that the source may be varying by 50% over the period of 1 year. It is clear that more observations are needed at X-ray frequencies, particularly at GHz frequencies, to see whether there is any systematic variation with respect to previous observations.

It is well known that for a relativistically expanding radio source the inverse-Compton radiation is drastically reduced (Rees 1966; Rees and Simon 1968). Taking the maximum possible variability, 50% in one year, we find that the compact cloud (component II) cannot be expanding faster than 1–2% the speed of light. Even for the maximum size allowed by the VLBI observations, the velocity of expansion cannot exceed 30–40% the speed of light.

It is therefore seen that if there is any expansion of compact cloud(s) in the nucleus of Cygnus A, this expansion is not relativistic. We note that such expansion velocities are too small to make any difference on the computed inverse-Compton emission or for that matter on the appearance of the synchrotron spectrum. The transition for the optically thick to the optically thin region of the synchrotron spectrum of an expanding source becomes gradual (resembling the spectrum of the compact source in Cygnus A) only for values of v/c close to 1 (van der Laan 1971); hydrodynamical calculations do not seem to alter this result (Vitello and Pacini 1977).

Mushotzky (1977) has constructed a synchrotron self-Compton model for NGC 4151 and NGC 1275 (3C 84); similar considerations apply to 3C 390.3 and 3C 273 and presumably to other compact, variable sources. These compact sources are characterized by flat X-ray spectra, strong optical emission line spectra, and a compact radio or millimeter component. According to Mushotzky (1977), a sudden injection of a large number of relativistic particles would result in an X-ray flare for which the rise time is that of the filling of the compact region by relativistic electrons and the decay time is that of the synchrotron losses—or even shorter, if the inverse-Compton lifetime is shorter than the synchrotron lifetime.

The rise time for component II (see Table 2) is about 70 days whereas the decay time is less than a year. Those lifetimes are certainly in agreement with the possible X-ray variability. It is interesting to note that if the interpretation given in § IV is correct, we expect that the larger cloud (component I) would not exhibit a variability as strong as the smaller cloud (component II). One would then expect that at radio frequencies above $\sim$20 GHz the flux would vary in a similar fashion to the X-rays, but below that frequency it would not. On the other hand, if the IR is due to emission by cold dust, it should not exhibit a variability. No variability is expected at optical wavelengths, except perhaps in the UV where there may be some nonthermal contribution: We note that the total contribution of components I and II, when the spectral break is taken into account (see Table 2), at 10^{15} Hz, or 3000 Å, is $\sim 4 \times 10^{-4}$ Jy, which may be larger than any thermal contribution at those wavelengths; this, of course, will happen only if the synchrotron spectra extend all the way to the UV.

It is interesting to compare the spectrum of the central source in Cygnus to the spectra of variable, compact radio sources. Such a comparison is shown in Figure 2, where the spectrum of the central source in Cygnus A is shown along with those of two famous variable sources: 3C 120 (a Seyfert galaxy of type 1) and 3C 273 (a quasar). The 3C 120 and 3C 273 radio and IR data and the X-ray data of 3C 120 are from Schnopper *et al.* (1977). The *UBV* fluxes are from Sandage (1972). The X-rays of 3C 273 are from Culhane (1977). Finally, the Cygnus A data are from Hobbs *et al.* (1978). The similarity of the spectra of the three sources at all frequencies is striking! Considering that 3C 120 is at a distance of 190 Mpc, compared to 323 Mpc for Cygnus A, the power of the central source in Cygnus A would rival that from 3C 120 and would actually be more luminous than 3C 120 at X-rays—if it can be demonstrated without doubt that the X-rays are coming from a compact source in the nucleus of Cygnus A. The total X-ray power in the 2–10 keV range could be as high as 10^{45} ergs s^{-1}, making the central source in Cygnus A primarily *an X-ray compact source* and only a few times weaker in X-rays than 3C 273! Schnopper *et al.* (1977) encounter the same difficulties that we did in fitting the IR and optical data for 3C 120. One can see from Figure 2 that the optical fluxes from Cygnus A drop off faster than those for 3C 120 and 3C 273, and this can be understood if thermal processes dominate in Cygnus A at optical wavelengths. At UV or lower wavelengths, though, the situation may be reversed.

Figure 2 demonstrates a great similarity between the spectra of these three famous objects—among the strongest of each of their types. This similarity is suggestive not just of variability for the central source in Cygnus A but also of a common origin and mechanisms of radiation for radio galaxies, Seyfert galaxies, and quasars.

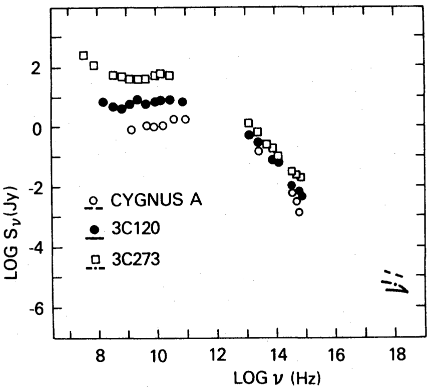

FIG. 2.—Comparison of the electromagnetic spectrum of the central source in Cygnus A with that of 3C 120 (type 1 Seyfert) and 3C 273 (quasar). Cygnus A data from Hobbs *et al.* (1978). 3C 120 and 2C 273 radio and IR data from Schnopper *et al.* (1977). 3C 120 X-ray data from Schnopper *et al.* (1977). All *UBV* fluxes are from Sandage (1972). 3C 273 X-ray data from Culhane (1977).

VI. CONCLUSIONS

Single component models as well as double component models have been explored in trying to fit the electromagnetic spectrum of the central source in Cygnus A. The single cloud models have the advantage that relatively few parameters have to be assumed (the size, whether or not the IR can be explained by the synchrotron process, and a particular electron spectrum, although the results do not depend very much on the shape of the assumed electron spectrum); however, in order to explain the slight rise at radio frequencies, a low-energy cutoff of the electron spectrum must be postulated. This minimum energy of the electron spectrum is found to be a fraction of a GeV, but its origin is unknown. Single cloud models fit the radio points but fail to fit the IR and the X-rays—if indeed the X-rays are from the central source in Cygnus A. A better fit of the IR or X-rays can be obtained, but one then requires *in situ* production or continuous acceleration of the electrons to offset the severe (primarily inverse Compton) losses. If this is not the case, and we regard these requirements as extra assumptions that may not be easily justifiable, the IR would have to be due to emission from cold dust. Such emission has been proposed by other workers for Cen A and Seyfert galaxies. The X-rays from Cygnus A would have to arise by some other way, perhaps thermal emission in a dense, compact cloud. If the X-rays are from the Cygnus A cluster, then this cluster would have to be one of the richest ones both in intracluster gas and in the numbers of galaxies; no such claim has been made in the literature.

Double component models have also been examined. Each cloud is optically thick to synchrotron radiation below a particular frequency and thin above it. Such models are not unique; however, they can account for the radio (synchrotron) as well as the X-rays (synchrotron self-Compton process). The X-rays must arise in the smallest cloud. Short synchrotron, inverse-Compton as well as diffusion times of the electrons are found for component II (the smallest of the two clouds). Such models, therefore, account for the variability of Cygnus A that may already have been detected in X-rays. No variability is expected in the IR, because this radiation cannot be synchrotron unless *in situ* production or continuous acceleration is again postulated; most likely the IR arises in cold dust that surrounds the central source. No variability is expected in the optical part of the spectrum, except perhaps in the UV, because thermal processes are suspected to be dominant at optical wavelengths. Finally, variability is expected at radio frequencies higher than, say, 20 GHz. Such variability should correlate with the X-rays. It is fortunate that at high frequencies any variability would be easier to detect due to the diminished contribution of the radio lobes.

The striking resemblance of the central source in Cygnus A to other active nuclei of galaxies (Seyferts and quasars) when their spectra are compared, argues in favor of common mechanisms of radiation and origin as well as variability for Cygnus A. That such variability has not been reported up to now in the radio is not surprising due to the difficulty in observing the central source over the much stronger radio lobes. Careful monitoring of the radio source over a period of a year or more, at frequencies higher than 20 GHz, would be very important. Also, more measurements of the IR are needed to see whether cold dust is responsible for the IR. Finally, it should be established once and for all whether the X-rays are coming from the same central source and whether variability is present at X-ray frequencies.

On the basis of the present work, the importance of the central source in Cygnus A is established, which up to now had not been realized due to the complete dominance of the radio lobes below 100 GHz. The small, and weak, central radio source may be emitting as much power as the strong radio lobes but at much higher than radio photon energies. Most likely, it is similar to other compact, active radio sources in Seyfert galaxies and quasars.

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APPENDIX A

In this appendix, the dependence of the various physical parameters of a radio cloud on the angular size is given. It is assumed that equations (2), (3), and (4) hold. From them, H, E_1, and N_0 can be found; the angular size is assumed to be a parameter that may vary either because it may be not known or because it may be computed from a fourth relationship (e.g., eq. [5]).

The various parameters of the radio cloud depend on the angular size, θ, as follows. These results do not depend on the electron index γ. Once, therefore, the parameters have been computed for a particular value of the angular size they may be computed for any other size:

Magnetic field: $H \propto \theta^{-6/7}$; (A1)

Electron energy at the low-energy cutoff of the electron spectrum: $E_1 \propto \theta^{3/7}$; (A2)

Number density of relativistic electrons: $n_e \propto \theta^{-15/7}$; (A3)

Synchrotron lifetime: $t_S \propto \theta^{9/7}$; (A4)

Inverse-Compton lifetime: $t_C \propto \theta^{11/7}$; (A5)

Energy density of photons: $U_{\rm ph} \propto \theta^{-2}$; (A6)

Ratio of total synchrotron to inverse (self)-Compton power: $E^{\rm SC} \propto \theta^{-2/7}$; (A7)

Optical depth for the synchrotron self-absorption: $\tau_s \propto \theta^{-2/7}$. (A8)

The total synchrotron power does not depend on θ.

If the X-rays are due to a hot gas, the electron density of this thermal gas and the free-free optical depth are

$$n_e \propto \theta^{-3/2}, \qquad \tau_{\rm ff} \propto \theta^{-2}. \tag{A9}$$

Finally, the break frequency of the synchrotron spectrum is (see eq. [5])

$$\nu_b = \frac{2.3H_0(\theta/\theta_0)^{-6/7}}{(t_{\rm yr}{}^2)_0(\theta/\theta_0)^2[H_0{}^2(\theta/\theta_0)^{-12/7} + 8\pi(U_{\rm ph})_0(\theta/\theta_0)^{-2}]^2}, \tag{A10}$$

where H_0, $(U_{\rm ph})_0$, and $(t_{\rm yr})_0$ are for an angular size θ_0.

APPENDIX B

The synchrotron radio luminosity of the source can be written as (cf. van der Laan and Perola 1969)

$$L_S = 1.55 \times 10^{-3} V N_0 H^2 \frac{E_2{}^{3-\gamma} - E_1{}^{3-\gamma}}{3-\gamma} \text{ ergs s}^{-1} \quad (\gamma \neq 3),$$

or

$$L_S = 1.55 \times 10^{-3} V N_0 H^2 \ln (E_2/E_1) \text{ ergs s}^{-1} \qquad (\gamma = 3), \tag{B1}$$

where E_1 and E_2 are the minimum and maximum energies, respectively, of the electron spectrum and where V is the volume of the radio cloud in cm^3. It is interesting to note that the quantity L_S does not depend on the value of the angular size θ (see Appendix A). This is not surprising since L_S is directly obtained from the observations. It can be obtained by integrating the flux density over all frequencies and then multiplying by $4\pi D^2$, where D is the distance to the radio source.

The relativistic electron density n_e can be written as

$$n_e = N_0(E_2{}^{1-\gamma} - E_1{}^{1-\gamma})/(1-\gamma). \tag{B2}$$

The photon energy density in the radio cloud is (see Appendix C)

$$U_{\rm ph} = \frac{9L_S}{16\pi R^2 c}, \tag{B3}$$

where R is the radius of the radio cloud and c is the speed of light.

The synchrotron and inverse-Compton (in this case self-Compton) lifetimes are, respectively (cf. Flasar and Morrison 1976; Tucker 1975),

$$t_S \sim \frac{0.013}{H^2 E(\mathrm{GeV})}\,\mathrm{yr}\,, \qquad t_C \sim \frac{4.88 \times 10^{-4}}{U_{\mathrm{ph}} E(\mathrm{GeV})}\,\mathrm{yr}\,. \tag{B4}$$

Finally, the ratio of the total power radiated by the inverse-Compton scattering of the electrons off the radio photons, L_C, to the radio power radiated by the synchrotron process, L_S, is

$$E^{\mathrm{SC}} \equiv \frac{L_C}{L_S} = \frac{U_{\mathrm{ph}}}{U_H} = \frac{9L_S}{2R^2H^2c}\,, \tag{B5}$$

where U_H is the energy density of the magnetic field. Expressions (B3) and (B5) are somewhat different from those found in other works (e.g., Hoyle, Burbidge, and Sargent 1966; Ginzburg and Syrovatskii 1964) because it is assumed here that the luminosity arises in an optically thin cloud where each point contributes equally to the luminosity (see Appendix C).

APPENDIX C

In this appendix we give the relationship between the luminosity L, the radius R, and the average energy density of the photon field U_{ph} in three different cases.

1. Point source of luminosity L, at the center of an optically thin sphere of radius R (Ginzburg and Syrovatskii 1964; Felten and Morrison 1966):

$$U_{\mathrm{ph}} = \frac{3L}{4\pi R^2 c}\,. \tag{C1}$$

2. Optically thick source (isotropic distribution of photons within the volume of the source) (cf. Hoyle, Burbidge, and Sargent 1966):

$$U_{\mathrm{ph}} = 4\pi I/c\,. \tag{C2}$$

But the flux F is given by $F = \pi I$, where $F = L/4\pi R^2$; therefore

$$U_{\mathrm{ph}} = L/\pi R^2 c\,. \tag{C3}$$

3. Optically thin source and L comes uniformly from the entire sphere. Integration over the entire sphere is required. Calling ϵ the volume emissivity (in ergs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$) and $I(\theta)$ the intensity at some angle θ, where we integrate over θ, we have

$$I(\theta) = \epsilon s(\theta) \qquad \text{and} \qquad U_{\mathrm{ph}}(r) = \frac{1}{c}\int I d\Omega\,, \tag{C4}$$

where $s(\theta)$ is the length of the chord at the direction θ (total path length through the sphere at the angle θ), and it is equal to

$$s(\theta) = (R^2 - r^2 \sin^2\theta)^{1/2} + r\cos\theta\,, \tag{C5}$$

where r is the distance of the particular point away from the center and integration over r is also performed. From (C4) we obtain

$$U_{\mathrm{ph}}(r) = \frac{2\pi\epsilon}{c}\int_{-1}^{+1} [(R^2 - r^2 + r^2x^2)^{1/2} + rx]dx\,, \tag{C6}$$

where $x = \cos\theta$. To find U_{ph} we average over the entire sphere

$$U_{\mathrm{ph}} = \frac{\int_0^R U_{\mathrm{ph}}(r) 4\pi r^2 dr}{4/3\pi R^3}\,.$$

The result of this integration is

$$U_{\mathrm{ph}} = 3\pi\epsilon R/c\,; \tag{C7}$$

and since $\epsilon = 3L/(4\pi R^3 4\pi)$, it follows that (C7) becomes

$$U_{\mathrm{ph}} = \frac{3}{4}\frac{3L}{4\pi R^2 c}\,. \tag{C8}$$

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