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MILLIMETER AND SUBMILLIMETER OBSERVATIONS OF 3C 273

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ABSTRACT

We report the first detection of 3C 273 (1226+023) at wavelengths of 107, 240, and 400 μm together with contemporary measurements at 800 μm, 1.1, 1.9, 3.3, and 8.9 mm. These observations show that the continuum spectrum of 3C 273 can be extrapolated smoothly from the submillimeter to the infrared with a constant spectral index.

There is no evidence of thermal emission from dust. We show that the spectrum is consistent with optically thin synchrotron emission from a relativistic beam at a small angle to the line of sight.
Subject headings: infrared: sources — quasars — radiation mechanisms

I. INTRODUCTION

Although the quasar 3C 273 (1226+023) has frequently been observed at wavelengths around 1 mm, the region of the spectrum around 400 μm has, until recently, remained inaccessible. Improvements in the QMC/Oregon photometer sensitivity have now enabled us to make near-simultaneous measurements of 3C 273 at 2 mm, 1.1 mm, 800 μm, and 400 μm from the ground. We have combined these data with observations (*i*) at shorter wavelengths taken a few months later with the Kuiper Airborne Observatory (KAO) and (*ii*) with others at longer wavelengths obtained from the ground (Owen *et al.* 1978; Howard 1982; Henderson 1982). There is evidence that 3C 273 is not variable at infrared wavelengths (Neugebauer *et al.* 1979). We have therefore also used these older infrared data in constructing our single-epoch spectrum.

The millimeter-to-infrared spectrum may be characterized by two power laws with a break at millimeter wavelengths and an upper cutoff frequency in the infrared. We find this spectrum to be consistent with a model in which we are observing optically thin emission from a relativistic beam oriented nearly along the line of sight.

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II. OBSERVATIONS

The 2 mm observations were obtained with the NRAO millimeter continuum system (Radostitz *et al.* 1983) mounted at the Cassegrain focus of the 36 foot (11 m) dish at Kitt Peak on the nights of 1982 January 17 and 21. The beam size was 70″ FWHP, and the chop amplitude and frequency were 4′ and 9 Hz, respectively. Calibration was made directly with Mars which was only 5° away on the sky. The brightness temperature of Mars was taken as 206 K at 2 mm using the model of Wright (1976), which at this long wavelength is in good agreement with the absolute measurements of Ulich (1981) at 90 GHz.

The observations at 1100, 800, and 400 μm were made on the night of 1982 April 22 at the f/35 Cassegrain focus of UKIRT on Mauna Kea. FWHP beamwidths, obtained by scanning through Mars, were 55″, 58″, and 65″, respectively, at 400, 800, and 1100 μm. The chopping secondary of the telescope gave a beam separation of 140″; the chop frequency was 12.5 Hz. The QMC/Oregon photometer (Ade *et al.* 1983) was employed with narrow-band filters of characteristics shown in Robson (1982).

Mars was observed directly before and after 3C 273, which was within 3° (in late April) and was observed at transit; the Martian brightness temperatures were again based on the model of Wright (1976). Doubt has recently been cast on the validity of this model (Simpson *et al.* 1981) particularly at wavelengths below 100 μm. We estimate that this additional uncertainty of 10% in

TABLE 1

AIRBORNE OBSERVATIONS OF 3C 273

Effective Wavelength (μm) (1)	KAO Photometer (2)	Flux Density ($\pm 1\ \sigma$ statistical error) (Jy) (3)	Absolute Calibration Error (4)	Beam Width to Half-Power Points (arcsec) (5)	Chopper Throw (arcmin) (6)	Calibration Object (7)	Date 1982 May (8)
58	G2	-0.5 ± 1.0	10%	33	2	Uranus	16
107	H1	2.0 ± 0.6	15%	33	3	Mars	8
240	H1	3.0 ± 0.4	15%	85	3	Mars	8

Martian flux density is within our errors of 15% which we allow for absolute calibration. The calibration procedure to determine the mean wavelength of observation and the derived flux for 3C 273 is described by Rowan-Robinson, Clegg, and Ade (1975) and Cunningham *et al.* (1981). Because we use narrow-band filters, the assigned fluxes and wavelengths are rather insensitive to the value of the spectral index. We used the value of -0.7 for the final calculations. Note that although these 2 mm and submillimeter observations were separated by 3 months, we also measured 3C 273 at 1100 and 800 μm in 1982 February and obtained very similar fluxes (9.0 ± 1.1 Jy and 7.1 ± 1.1 Jy, respectively).

Far-infrared observations at effective wavelengths of 58 μm, 107 μm, and 240 μm were made in 1982 May with the University of Chicago G2 and H1 photometers on the Kuiper Airborne Observatory (KAO). Details of the observations are listed in Table 1. Uncertainties quoted in column (3) are statistical errors. In column (4), we give the estimated error in the absolute calibration. Further details on the photometers may be found in Keene *et al.* (1983).

We have combined our data with measurements made at 3 mm by R. Howard (1982) also using the NRAO 36 foot antenna on 1982 January 31 and with measurements at 8.96 mm by Henderson (1982) using the Chilbolton 25 m dish on 1982 March 28; these data are also presented in Table 2. We have added ground-based data taken at near- and mid-infrared wavelengths by Neugebauer *et al.* (1979). Since these authors present evidence that the infrared emission of 3C 273 did not vary by more than 20% over a period of 10 years, we feel justified in using these near- and mid-infrared data for our spectrum. Finally, we have added a single-epoch radio spectrum from Owen *et al.* (1978) taken when the 90 GHz flux was very similar to our 1982 value. Figure 1 shows the overall millimeter-to-infrared spectrum of 3C 273 as constructed for this epoch. Also shown inset in Figure 1 are millimeter and submillimeter data for 3C 273 taken approximately 1 year earlier. The data were obtained from the same telescopes as previously described and are also tabulated in Table 1. It is evident from this comparison that significant submillimeter spectral changes have not occurred during this period.

Figure 1 shows that, between 30 cm and 3 μm, the spectrum may be represented by two power laws: A flattish spectrum with spectral index $\alpha = -0.1$ ($S_\nu \propto \nu^\alpha$) steepening near 5 mm to a spectrum with $\alpha = -0.7$. At wavelengths shorter than 3 μm there is a rapid cutoff in the spectrum down to the optical continuum (Puetter *et al.* 1982).

We emphasize that the index of -0.7 has been determined *solely* by our measurements at 2 mm, 1.1 mm, 800 μm, and 400 μm. It can be seen that this spectrum continues through the independent KAO, 20 μm, and 10 μm points. Finally, it will be noted that there is no

TABLE 2

GROUND-BASED OBSERVATIONS OF THE MILLIMETER-WAVE CONTINUUM SPECTRUM OF 3C 273

Effective Wavelength (mm)	Mean Frequency (GHz)	Bandwidth (GHz)	Epoch	Flux (Jy)	Standard Error
8.96	34	1	1981.41	30.0	0.4
			1982.24	31.3	0.4
3.30	91	1	1981.21	26.0	1.0
			1982.08	18.0	1.0
1.90	158	45	1981.21	19.0	2.0
			1982.05	14.5	1.4
1.10	273	84	1981.13	11.0	1.0
			1982.30	9.9	0.4
0.79	381	120	1981.13	8.7	1.5
			1982.30	7.3	0.4
0.39	773	290	1982.30	4.9	0.9

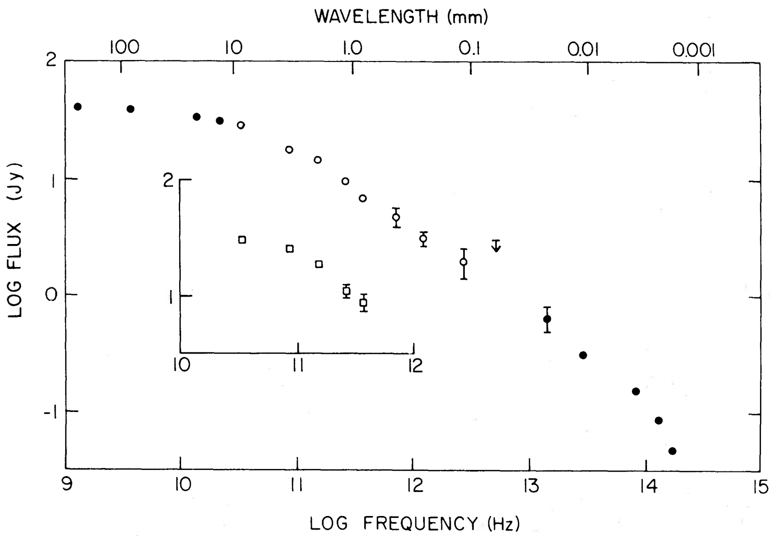

FIG. 1.—The radio to infrared spectrum of 3C 273. Filled circles are from Owen *et al.* (1978) and Neugebauer *et al.* (1979). Open circles represent our 1982 millimeter and submillimeter data. The 1981 millimeter and submillimeter spectrum is shown displaced for clarity. Error bars shown in the figure represent the quadratic sum of the statistical and the calibration errors.

evidence for a submillimeter excess such as could be caused by thermal emission from dust (Telesco and Harper 1980).

III. DISCUSSION

The number of models of quasar emission appearing in the literature reflects the lack of sufficient data to discriminate unambiguously between them. Rather than attempt a comprehensive discussion of all the different alternatives, we have chosen to compare our data for consistency with only two of the basic models; because of the apparent superluminal expansion observed in 3C 273, we believe that any realistic model must include some degree of relativistic beaming. Once we have described the two selected models and derived parameters for each from our data, we shall conclude with suggestions for future observations which may help further in distinguishing between them.

Model A.—In 3C 273, we have seen that the continuum spectrum between 30 cm and 5 mm has spectral index $\alpha = -0.1$; this flat part of the spectrum may be explained as a superposition of a number of self-absorbed, synchrotron components (see, e.g., Marscher 1980*a* and references therein). In this case, the steepening of the spectrum observed near $\lambda = 5$ mm is the result of a transition to the optically thin regime. The observed slope, $\alpha = -0.7$ (see Figs. 1 and 2*a*), corresponding to an energy distribution $N(E)dE \propto E^{-2.4}$, is similar to that in many other classes of optically thin synchrotron sources (e.g., Ginzburg and Syrovatskii 1964; Moffet 1975; see also Landau *et al.* 1983). The second spectral steepening observed at 3 μm may be caused either by a high-energy cutoff in the synchrotron energy spectrum or by adiabatic expansion losses. The brightness temperature in the rest frame of a compact source, T_m^*, is limited to a maximum value $\sim 10^{12}$ K by the synchrotron-self-Compton mechanism, and the angular radius of a self-absorbed source is given by (Condon *et al.* 1981):

$$\frac{\phi}{\text{mas}} = \left\{0.02\left[\left(\frac{S_\nu{}^0}{\text{mJy}}\right)\left(\frac{S_\nu{}^r}{\text{mJy}}\right)^{2(2-\alpha_0)}\left(\frac{\nu_0}{\text{GHz}}\right)^{-\alpha_0} \times \left(\frac{\nu_r}{\text{GHz}}\right)^{5(\alpha_0-2)}\right]^{1/2(5-2\alpha_0)}\right\} \Big/ \left[\frac{T_m{}^*}{10^{12}\text{ K}}(1+z)\right]^{1/2},$$

where, in this case $\nu_0 = 2800$, $S_\nu{}^0 = 2.3 \times 10^3$, $\alpha_0 = -0.7$, $\nu_r = 34$, $S_\nu{}^r = 31.3 \times 10^3$, $z = 0.158$, so if $T_m{}^* \sim 10^{12}$ K, $\phi \sim 0.1$ mas. The magnetic field in a self-absorbed homogenous synchrotron source is given by (Burbidge, Jones, and O'Dell 1974)

$$B = \frac{2\pi mc}{e}\frac{\nu_m}{\gamma_m{}^2}(1+z),$$

where ν_m is the turnover frequency and γ_m is the characteristic Lorentz factor for electrons radiating at that frequency, i.e.,

$$\gamma_m = \frac{S_m(1+z)}{2i_{\alpha 0}\, m\nu_m{}^2\Omega},$$

$i_{\alpha 0}$ is a dimensionless function of spectral index α, tabulated in Jones, O'Dell, and Stein (1974): for $\alpha = -0.7$, $i_{\alpha 0} = 0.22$. Ω is the solid angle of the source and S_m is the flux density (30 Jy) at $\nu_m = 60$ GHz.

For $\phi \sim 0.1$ mas we obtain $\gamma_m \sim 326$ and $B \sim 0.2$ G, which strengthens the argument that the X-ray and γ-ray emission of 3C 273 is first- and second-order self-Compton emission from the compact synchrotron source, as significant *n*th-order Compton emission is expected at frequencies $\nu_c \sim \gamma^{2n}\nu_m$, where ν_m is the peak of the synchrotron emission and γ is the Lorentz factor of the electrons.

Model B.—Second, we consider the discussion by Marscher (1980*b*) of the relativistic beam model of

Blandford and Rees (1974). The crucial difference between models A and B occurs in the interpretation of the flat part of the observed continuum spectrum. In model B the slope of $\alpha = -0.1$ arises from an *optically thin* synchrotron component of energy distribution $N(E)dE \propto E^{-1.2}$. In this model three main regions of flow for the beam are distinguished: (1) For $R < R_*$, where R_* is the distance from the central machine at which the flow becomes sonic, we have a turbulent region with a consequently disordered magnetic field; (2) for $R_+ > R > R_*$ we have a well defined, accelerating, relativistic beam of diameter $r \propto R^\epsilon$ where ϵ is small; and (3) for $R > R_+$, where R_+ is the distance at which the protons become nonrelativistic in the rest frame of the beam bulk motion, we assume the beam becomes free, rapidly widening, and with particle energies decreasing rather rapidly in the radial direction.

We tentatively assign the origin of the 30 cm to 3 μm spectrum of 3C 273 to the region (2) of the beam, the underlying optical-to-γ-ray continuum to region (1), and the longer radio wavelengths to region (3) and to the halo which surrounds the compact core of 3C 273. Figure 2*a* summarizes schematically the spectral information we have available.

The observed properties of such a beam model depend upon the angle of viewing. Because apparent superluminal motion is observed in 3C 273 (Pearson *et al.* 1981) we assume we are observing the beam at a small angle $\theta \approx \Gamma^{-1}$, where Γ is the bulk Lorentz factor of the jet. For this case, confining our attention to emission

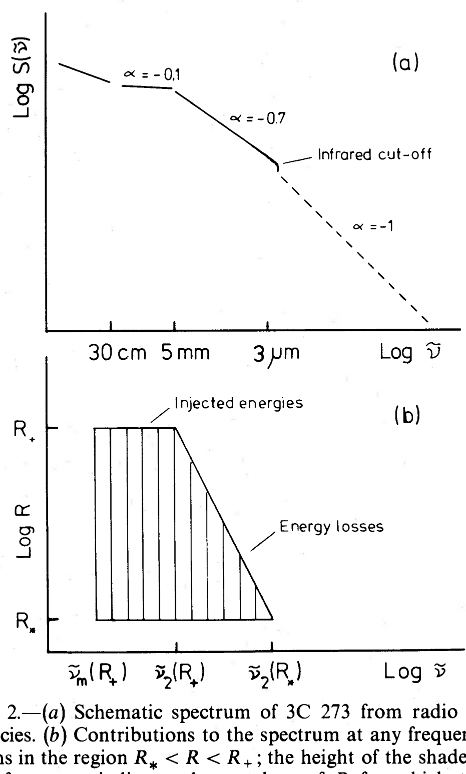

FIG. 2.—(*a*) Schematic spectrum of 3C 273 from radio to γ-ray frequencies. (*b*) Contributions to the spectrum at any frequency from electrons in the region $R_* < R < R_+$; the height of the shaded region at any frequency indicates those values of R for which there are electrons radiating at that frequency.

from the region $R_* < R < R_+$, we may summarize the overall properties of the spectrum. The highest frequency observed is $\tilde{\nu}_2(R_*) = D_* \nu_2(R_*)$ corresponding to the highest electron energy left by synchrotron losses by the time the beam reaches R_*; here ν denotes a frequency in the rest frame of the beam, $\tilde{\nu}$ a frequency in the observer's frame, and $D = \Gamma^{-1}(1 - \beta\cos\theta)^{-1}$ is the bulk Doppler factor of the beam.

For $\tilde{\nu}_2(R_+) < \tilde{\nu} < \tilde{\nu}_2(R_*)$, the spectrum is steepened, over that resulting from the initial particle energy spectrum, by a combination of adiabatic expansion and synchrotron losses; $\tilde{\nu}_2(R_+)$ is the observed frequency corresponding to the highest particle energy remaining at R_+. Finally for $\tilde{\nu}_m(R_+) < \tilde{\nu} < \tilde{\nu}_2(R_+)$, ν_m being the frequency at which the radiation becomes optically thick, the electrons have lost little energy and the spectrum reflects the injected particle spectrum.

These conclusions are summarized in Figure 2*b* which identifies the frequencies $\tilde{\nu}_2(R_+)$ and $\tilde{\nu}_2(R_*)$ with wavelengths of 5 mm and 3 μm, respectively, and assumes that $\tilde{\nu}_m(R_+) \lesssim 1$ GHz. Figure 2*b* also shows the range of R contributing to any given observed frequency. It follows from Marscher (1980*b*) that the dominant contribution to the flatter part of the optically thin spectrum comes from R_+.

The observed superluminal velocity in 3C 273 is 5.3*c* (Pearson *et al.* 1981), assuming $H_0 = 100$ km s^{-1} Mpc^{-1}, and this sets a lower limit of ~ 5.4 to the bulk Lorentz factor Γ_+ of the beam at R_+ with a corresponding value $\theta_m = \cot^{-1} 5.3 \approx 11°$ for the angle θ between the line of sight and the direction of the beam. $\Gamma_* = 1.22$, on the other hand, since the flow is sonic ($\beta_* = 1/\sqrt{3}$) at R_*, and $D_* = \Gamma_*^{-1}(1 - \beta_* \cos\theta) \approx 1.9$.

For $\tilde{\nu}_m(R_+) < \tilde{\nu}_2 < \tilde{\nu}_2(R_+)$ we have $S_\nu \propto \nu^\alpha$, where $\alpha = -(s-1)/2$ (Marscher 1980*b*; all further relations are from this reference unless otherwise stated), s being the index of the injected particle spectrum: from the spectrum we deduce $s = 1.2$ (see above).

For $\tilde{\nu}_2(R_+) < \tilde{\nu} < \tilde{\nu}_2(R_*)$ we have $\alpha = -(1-\epsilon)/3\epsilon$, provided that $\epsilon > \frac{1}{6}$ so that adiabatic expansion losses dominate, giving $\epsilon = 0.32$.

The relation between the breakpoints $\tilde{\nu}_2(R_*)$ and $\tilde{\nu}_2(R_+)$ is predicted to be

$$\frac{\tilde{\nu}_2(R_*)}{\tilde{\nu}_2(R_+)} \approx \frac{D_*}{D_+}\left(\frac{\Gamma_+}{\Gamma_*}\right)^4 ,$$

and this has a minimum value of ~ 130 compared with the observed value of 5 mm/3 μm ~ 1700. It is easily shown, however, that the predicted value of $\tilde{\nu}_2(R_*)/\tilde{\nu}_2(R_+)$ can be raised by an order of magnitude by allowing θ to increase from its optimum value of $\sim 11°$ to $\sim 19°$. There is, of course, no necessity for us to be viewing at the angle required for minimum bulk Lorentz factor. We adopt a value of 19° in what follows.

We estimate the radial distances R_* and R_+ as follows. We assume that the smallest structure identifiable on the 5.0 GHz VLBI maps of Readhead *et al.* (1979) sets an upper limit to the projection of R_+ since we assume that this lower frequency radio emission originates beyond R_+. Taking this structure to be 10^{-2} arcsec and the distance of 3C 273 ($H_0 = 100$ km s^{-1} Mpc^{-1}) to be 474 Mpc, we obtain a value of $R_+ < 70$ pc. Since $R \sim \Gamma^{1/\epsilon}$, we deduce $R_* < 0.3$ pc. This underlines why we should only combine observations taken within a time scale of no more than a few months (see, e.g., Epstein *et al.* 1982; Sherwood *et al.* 1983).

Finally, we estimate the magnetic fields within the source. We have

$$B_*^{\,3}(\mathrm{G}) \gtrsim \frac{10^8 D_* \Gamma_*^{\,2} \beta_*^{\,2}}{\tilde{\nu}_2(R_*) R_*^{\,2}(\mathrm{pc})},$$

which gives $B_* \gtrsim 22 \times 10^{-3}$ G. As $B \sim \Gamma^{-2}$ we deduce that $B_+ = 0.5 \times 10^{-3}$ G.

It may be objected that model B is similar to that usually proposed for "blazars" (e.g., Ennis, Neugebauer, and Werner 1982) rather than the less violent radio-loud objects like 3C 273 for which it is often deduced that $\theta \gg \Gamma^{-1}$. We remark, however, that we need a small value of θ to explain superluminal motion, and that although small θ is probably a necessary condition for violent variability, it is not necessarily sufficient. On the other hand, we might expect relatively strong polarization to arise from the jet because this is likely to be the most ordered part of the source. Such submillimeter polarization data are lacking at present, but it is interesting to note that Rudnick *et al.* (1978) find 3C 273 to be more polarized at millimeter wavelengths (5.8% at 3 mm) than at centimeter wavelengths (2.4% at 11.1 cm). Observations of the degree of submillimeter polarization are clearly desirable.

It may be possible to explain the underlying optical-to-γ-ray continuum as optically thin emission of the central energy machine, i.e., the region $R < R_*$. However, a naive interpretation of this model would lead one to suppose that the spectral index in this region would be the same as that between $\nu_m(R_+)$ and $\tilde{\nu}_2(R_+)$, since we have attributed this region of the spectrum in model B to an unmodified particle energy spectrum. In fact the high frequency spectral index is -1, much steeper than the value of -0.1 seen in the millimeter region so that, unless the particle-energy spectrum is somehow flattened between the central region and R_*, it may well be more realistic to attribute the X- and γ-ray emission in model B (as in model A) to synchrotron–self-Compton radiation from the relativistic beam (e.g., Königl 1981).

Clearly our discussion is tentative. We hope, nevertheless, to have demonstrated the important rôle accurate, simultaneous, multifrequency photometry can play in the modeling of quasar emission. In order to distinguish between the two models we have discussed, it will be necessary to monitor the spectrum in several wavebands from radio through to at least the submillimeter region.

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