THE ASTROPHYSICAL JOURNAL, 278:521–529, 1984 March 15

TWO MULTIFREQUENCY OBSERVATIONS OF 3C 371

D. M. WORRALL[1] AND J. J. PUSCHELL[2]
Center for Astrophysics and Space Sciences, University of California, San Diego
F. C. BRUHWEILER[1]
Physics Department, Catholic University of America
H. R. MILLER
Department of Physics and Astronomy, Georgia State University
R. J. RUDY
Steward Observatory, University of Arizona
W. H.-M. KU
Columbia Astrophysics Laboratory, Columbia University
M. F. ALLER, H. D. ALLER, AND P. E. HODGE
Radio Astronomy Observatory, University of Michigan
K. MATTHEWS, G. NEUGEBAUER, AND B. T. SOIFER
Palomar Observatory, California Institute of Technology
AND
J. R. WEBB, A. J. PICA, J. T. POLLOCK, A. G. SMITH, AND R. J. LEACOCK
Department of Astronomy, University of Florida
Received 1983 June 9; accepted 1983 August 30

ABSTRACT

We present observations of 3C 371, made at frequencies from the radio to the ultraviolet, which were coordinated during two short time intervals separated by 3 months. We also present 1 keV X-ray flux densities measured at a different time. The multifrequency measurements indicate spectral steepening at visual wavelengths, and that an extrapolation of the ultraviolet continuum falls below the X-ray data. We explain the infrared through X-ray data as relativistically beamed synchrotron self-Compton emission and derive source parameters for two possible models. Our ultraviolet spectra both show strong Lyα emission at the same redshift as weak optical emission lines reported previously. We favor production of these lines by recombination of gas after its ionization by the ultraviolet to X-ray continuum radiation. We tentatively identify C IV and N V absorption lines in one of our ultraviolet spectra, which, if real, suggest the presence of a hot ($\sim 3 \times 10^5$ K) gaseous halo in 3C 371.

Subject headings: BL Lacertae objects — galaxies: individual — radio sources: galaxies — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

The N galaxy 3C 371, at a redshift of 0.05 (Sandage 1966), has been described as a BL Lacertae object in the center of an elliptical galaxy (Miller 1975), due to its stellar absorption lines and the variability and polarization characteristics of its compact nucleus. Miller (1981) reported it to be in a visually bright phase, and soon thereafter we observed it with the *International Ultraviolet Explorer* (*IUE*) telescope in conjunction with ground-based observations at radio through visual wavelengths. We repeated observations 3 months later. The two observing periods will be referred to as the 1981 May and August epochs.

II. OBSERVATIONS

Tables 1–7 summarize the observations. The ultraviolet data have been corrected for reddening using the extinction law of Savage and Mathis (1979) normalized to $A_v = 0.13$ mag, the value derived from the method of Burstein and Heiles (1978). Measured visual and infrared magnitudes are given in Tables 2–6. For these wave bands, estimated contributions from the surrounding galaxy have been subtracted using the aperture-dependent visual magnitudes of Sandage (1973). We used the standard E galaxy values of Frogel *et al.* (1978) for extrapolation of these values to infrared wavelengths. The resultant core magnitudes have been corrected for reddening and converted to flux densities, f_Q, and are given in the last column of Tables 2–6. Tables 3, 5, and 6 also give the percentages of the measured flux density which is contributed by the galaxy. This peaks at 20%–30% for diaphragms larger than 7″ and wavelengths between about 0.4 and 2.3 μm. At longer infrared wavelengths it becomes negligible. Although Table 3 shows a 9% contribution at about 3600 Å, the flux from a standard elliptical galaxy plunges quite steeply at shorter wavelengths, and the galaxy contribution to the *IUE* measurements should be negligible at all but the longest wavelengths.

a) *IUE Measurements*

Low-resolution large-aperture–mode observations were made as described in Table 1. We improved upon the signal-

[1] Guest Observer with the *IUE* satellite.
[2] Now with Titan Systems, Inc.

TABLE 1

IUE Continuum Fits to f_ν (Jy) = $K\nu_{15}^{-\alpha}$

Date in 1981 (UT)	Camera[a]	α (1 σ error)	$K \times 10^3$ (1 σ error)[b]
May 1 0900–1558	SWP and LWR	1.74 ± 0.07	2.37 (+0.04, −0.05)
Aug 3 0226–0946	SWP	1.46 ± 0.16	1.34 (+0.03, −0.03)

[a] Frequency ranges—SWP: $\nu \approx 1.54$–2.50×10^{15} Hz; $\lambda = 0.12$–0.19 μm. LWR: $\nu \approx 0.94$–1.54×10^{15} Hz; $\lambda = 0.19$–0.32 μm.

[b] Corresponding to best fit value of α.

to-noise ratio of the *IUE* Standard Image Processing System spectrum by manually selecting a narrower extraction slit and thus including only those "line-by-line" data sets with measurable source contribution. This procedure minimizes contamination of the source spectrum by radiation hits on the SEC-vidicon camera face. We derived absolute flux densities using the Fahey-Klinglesmith FORTH software at GSFC. The data were corrected for galactic extinction using the method described above. No galaxy contribution was subtracted from the resultant spectra. We detected no obvious 2200 Å absorption feature whose presence might suggest that A_v is larger than the adopted value of 0.13 mag.

The source exhibited significant line features in the ultraviolet. Both the 1981 May and August spectra exhibit emission, identified as Lyman-α at a redshift of $z = 0.0520 \pm 0.0017$. This agrees with the redshift of $z = 0.0506 \pm 0.009$ determined from the visually observed emission lines (Sandage 1966; Miller 1975). The line fluxes for May and August are in good agreement and average 1.0×10^{-13} ergs cm^{-2} s^{-1}. The level of noise in the underlying continuum emission would imply that this flux estimate is accurate to about 30%. In the 1981 May spectrum (Fig. 1) we also identify absorption features of C IV (λ1550) and N V (λ1240) at redshifts of 0.0506 ± 0.0016 and 0.0491 ± 0.0013, respectively. The significance of these features is questionable, considering the level of continuum noise. However, they were noticed when the short-wavelength camera (SWP) image was read down from the *IUE* and viewed on the RAMTEC display unit. They were also seen on the *IUE*-furnished "photowrite." We estimate equivalent widths for the C IV and N V features of 6.1 ± 1.0 Å and 3.5 ± 1.0 Å, respectively. In 1981 August, 3C 371 was at ~65% of its May flux density level (Table 1), and the N V feature was not detected. Unfortunately, a radiation "hit" in the vicinity of redshifted C IV renders the August spectrum useless for confirmation of this absorption feature.

We fit the continua with single power-law spectra. For this we excluded SWP data at the Lyα, C IV, and N V features. For each of our three spectra we then constructed the average flux density at the mean wavelength of consecutive ~47 Å (SWP) and ~70 Å (long-wavelength camera: LWR) bins. We fit the binned data with a power law of slope α, where $f_\nu \propto \nu^{-\alpha}$. The minimum χ^2 was unacceptable for each of the three spectra

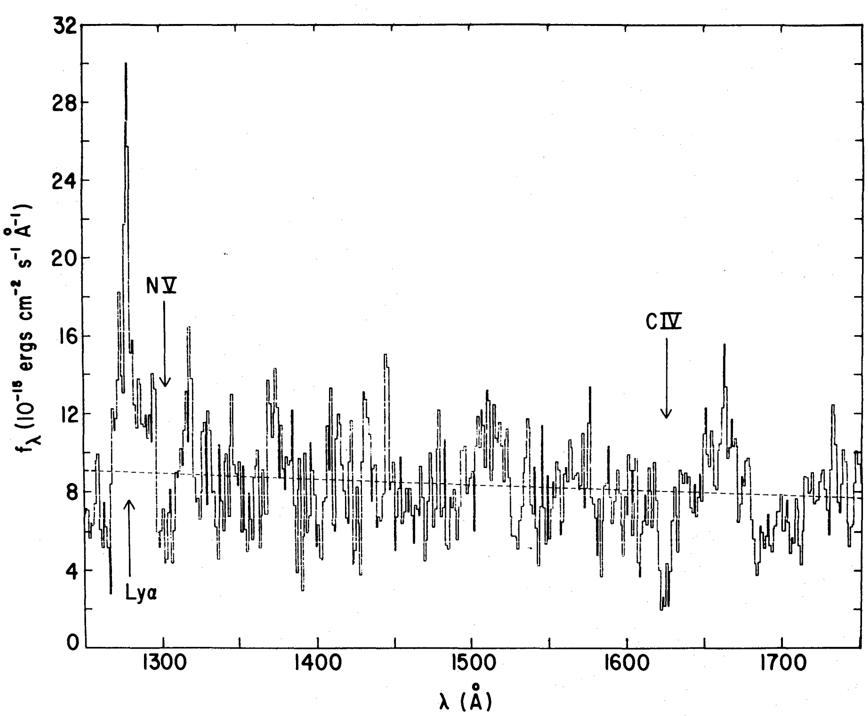

FIG. 1.—1981 May 1 1250–1750 Å observed spectrum of 3C 371 after correction for reddening using $A_v = 0.13$. The dashed line represents a power-law fit to the continuum. The bin width is ~20% of the instrumental resolution.

TABLE 2

IUE FES VISUAL MAGNITUDES (V_{gal} = 15.8 mag)

Date (UT) (mo/day/yr)	Measured m_v (mag)	f_Q (mJy)
05/01/81	14.5 ± 0.1	4.2 ± 0.4
08/03/81	14.8 ± 0.12	2.7 ± 0.3

and hence revealed the existence of an additional source of error. We account for this as being due to small systematic errors in the *IUE* photometric calibrations (Hackney, Hackney, and Kondo 1982). In order to assess more accurately the errors in our derived power law, we added in quadrature to the statistical error in each bin the constant additional percentage error which was necessary to produce an acceptable minimum χ^2, χ^2_m. The one-sigma range for α then corresponds to values for which χ^2 is $\leq \chi^2_m + 1$. The additional errors that we required were 11% for the combined SWP and LWR May spectra, and 9% for the August spectrum. Our errors on α are thus slightly larger than those given by Worrall and Bruhweiler (1982), where we did not take into account the additional systematic uncertainties. Results are given in Table 1. We use ν_{15} to denote frequency in units of 10^{15} Hz. The May and August spectral indices do not differ significantly, but the August flux is ~35% lower than the May value.

b) *Visual and Infrared Measurements*

The fine error sensor (FES) of the *IUE* was used to measure the visual magnitude immediately prior to the May and August SWP exposures (Table 2). The measurements indicate a significant decrease in core flux density (~36%) over the 3 month interval. We imaged a region of size 80″ × 72″ centered on 3C 371 in order to measure the FES magnitudes. We are thus confident that the flux density decrease is real and not the artifact of a spatial offset. The ultraviolet flux density decrease provides independent confirmation.

Photometric *UBV* observations were made using the number 2, 0.9 m, Kitt Peak National Observatory (KPNO) telescope in 1981 May (Table 3). The *V* fluxes agree with the FES value for May, and the source appears to have remained constant over this 10 day period. For these data ($m_v \approx 14.4$ mag), the spectral index through the core flux density is $\alpha = 1.5$. This agrees within errors to the previous reports of $\alpha = 1.7$ for $m_v \approx 14.1$ mag, $\alpha \approx 1.5$ for $m_v = 14.6$ mag (Oke 1978), and $\alpha = 1.35$ for $m_v \approx 15.1$ mag (Miller 1975).

Longer visual coverage of 3C 371 was accomplished using the photographic photometry system at the Rosemary Hill Observatory (Table 4). A complete description of the procedures for data acquisition and reduction is given by Pollock *et al.* (1979). Unfiltered 103a-O plates were used, which give photographic magnitudes, PG. The *B* − PG correction was found to be 0.65 ± 0.1 mag, from *B* and PG exposures of 1981 July 27 and 1982 May 22. The measurements are consistent with a constant flux density between 1981 June and October. There is an inconsistency between the flux density level of these data and the lower visual FES flux density for 1981 August.

TABLE 3

VISUAL PHOTOMETRIC OBSERVATIONS OF 1981 MAY WITH 0.9 METER KPNO TELESCOPE
(diaphragm diameter = 15″.5; V_{gal} = 15.74 mag, B_{gal} = 16.80 mag, U_{gal} = 17.29 mag)

Date (UT) (mo/day/yr)	Bandpass	Measured Magnitude (mag)	Galaxy % of Total Flux	f_Q (mJy)[a]
5/5/81	*U*	14.61	9	2.95 ± 0.15
	B	15.00	19	4.16 ± 0.21
	V	14.36	28	5.56 ± 0.28
5/7/81	*U*	14.63	9	2.90 ± 0.14
	B	15.03	20	4.01 ± 0.20
	V	14.41	29	5.21 ± 0.26
5/9/81..............	*U*	14.66	9	2.82 ± 0.14
	B	15.05	20	3.94 ± 0.20
	V	14.44	30	5.02 ± 0.25

[a] Measuring errors are ≤0.01 mag. 5% systematic errors assumed in f_Q due to flux conversion and galaxy subtraction.

TABLE 4

VISUAL PHOTOMETRIC OBSERVATIONS OF 1981 JUNE–OCTOBER WITH THE 0.76 METER ROSEMARY HILL OBSERVATORY TELESCOPE
(diaphragm diameter = 8″; B_{gal} = 17.2 mag, V_{gal} = 16.2 mag)

Date (UT) (mo/day/yr)	Bandpass	Measured Magnitude (mag)	f_Q (mJy) (corrected to *B* color)
6/4/81	PG	14.29 ± 0.11	4.78 ± 0.66
6/29/81	PG	14.58 ± 0.15	3.49 ± 0.58
7/6/81	PG	14.21 ± 0.07	5.19 ± 0.57
7/28/81	PG	14.58 ± 0.09	3.49 ± 0.42
7/28/81	*B*	15.27 ± 0.08	3.34 ± 0.25
7/28/81	*V*	14.32 ± 0.08	6.62 ± 0.49[a]
8/4/81	*B*	15.27 ± 0.11	3.34 ± 0.34
8/5/81	*V*	14.45 ± 0.10	5.71 ± 0.53[a]
8/5/81	*B*	15.20 ± 0.07	3.59 ± 0.23
8/25/81	PG	14.51 ± 0.23	3.76 ± 0.89
9/18/81	PG	14.68 ± 0.13	3.13 ± 0.46
10/20/81	PG	14.45 ± 0.04	4.01 ± 0.41

[a] *V* flux.

However, we feel that this is within the bounds of systematic error in comparing results from these different detector systems. We infer that the source's flux density remained relatively constant between June and October, but that there was a net flux density decrease between May and August, which presumably occurred during May.

Infrared observations were obtained for the May epoch with the 3 m Shane telescope at the Lick Observatory (Table 5). The observations were obtained with a liquid-helium–cooled InSb detector through discrete bandpasses using a 15″ chopper spacing. The August epoch observations were made with a solid-nitrogen–cooled InSb detector and a bolometer at the f/72 focus of the 5 m Hale telescope at Palomar Observatory (Table 6) using a 10″ chop in a north-south direction. The infrared fluxes for the two epochs agree. The spectral index, $\alpha \approx 0.7$, is flatter than that for the visual data.

c) Millimeter and Radio Measurements

The source was observed at 89.6 GHz on 1981 April 17 and 19 using the NRAO 11 m telescope on Kitt Peak.[3] The telescope beam covers 75″ on the sky with a pointing accuracy of 5″–10″. The two channels of the standard dual-channel cooled Cassegrain receiver were combined to give the best possible noise level, and standard beam-switching techniques were used. Pointing corrections were continuously updated from frequent observations of Jupiter, Venus, DR 21, and 3C 84. The brightness temperature to flux density calibration was based on the calibration of Ulich (1981). Corrections for atmospheric attenuation were based on regular observations of the sky temperature as a function of zenith distance. The April 17 and 19 flux densities agreed with each other, with a mean of 900 ± 125 mJy.

The University of Michigan 85 foot (26 m) paraboloid was used to measure flux densities at 4.8, 8.0, and 14.5 GHz around each of the May and August epochs. Aller, Aller, and Hodge (1981) describe the data collection and reduction systems. The results are given in Table 7. The source exhibited no significant variability at any of the frequencies, either between the two epochs or within each of them individually.

d) X-Ray Characteristics of the Source

Reports that 3C 371 was a relatively bright X-ray source came from observations with the *HEAO 1* satellite (Marshall *et al.* 1979; Snyder *et al.* 1982) with detectors of angular resolution of 1°–3°. The source was subsequently observed twice with the IPC on board the *Einstein Observatory*. The first observation, lasting 1441 s, was made on 1979 July 22.0; the second observation, lasting 841 s, was made on 1980 December 13.4. The 0.5–4.5 keV flux measured during both observations was consistent with a constant 2.2×10^{-12} ergs cm^{-2} s^{-1}. The 1 keV flux density was 0.6 μJy. The error is roughly 30%, due to uncertainties in the calibration of the *Einstein* IPC. The spectrum of the source was poorly determined. However, the hardness ratio (Zamorani *et al.* 1981), 0.8, suggests that the source is somewhat softer than 3C 273 ($\alpha > 0.4$): It is definitely not highly absorbed.

A variable (×4) soft X-ray source of comparable intensity, located 20′ to the SE of 3C 371, was observed during both pointings. This source at $\alpha = 18^h10^m28^s$, $\delta = 69°40'21''$ may be identified with a 9.4 mag K2 star. The X-ray to optical flux ratio of 4×10^{-3} to 1×10^{-3} is reasonable for a late-type star. If the ratio were 1×10^{-2} during 1977 September, the data of Marshall *et al.* (1979) and Snyder *et al.* (1982) may be explained by source confusion in the 1°–3° fields of view of these detectors. The star is closer to the centroid of the Snyder *et al.* error box than 3C 371.

Thus, the most consistent explanation for all the X-ray data

[3] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 5

INFRARED PHOTOMETRIC OBSERVATIONS OF 1981 APRIL 24 WITH THE 3 METER LICK OBSERVATORY TELESCOPE (diaphragm diameter = 7″62; V_{gal} = 16.26 mag)

λ (μm)	Measured Magnitude (mag)	Galaxy % of Total Flux	f_Q (mJy)
1.05	12.74 ± 0.1	25	11.3 ± 1.5
1.25	12.31 ± 0.1	28	13.0 ± 1.8
1.65	11.68 ± 0.1	31	15.1 ± 2.2
2.28	10.82 ± 0.1	20	23.3 ± 2.9

TABLE 6

INFRARED PHOTOMETRIC OBSERVATIONS OF 1981 JULY 22 WITH THE 5 METER HALE TELESCOPE AT PALOMAR OBSERVATORY (diaphragm diameter = 4″5; V_{gal} = 16.9 mag)

λ (μm)	Measured Magnitude (mag)	Galaxy % of Total Flux	f_Q (mJy)
1.25	12.61 ± 0.08	17	11.4 ± 0.9
1.65	11.83 ± 0.09	15	15.4 ± 1.5
2.20	11.04 ± 0.08	9	21.6 ± 2.0
3.50	9.88 ± 0.10	4	30.0 ± 3.0
10.10	6.74 ± 0.21	0	75.0 ± 16.0

TABLE 7

RADIO OBSERVATIONS

Date (UT) (mo/day/yr)	Frequency (GHz)	Flux Density f_R (Jy)	σ_f
4/20/81	14.5	2.06	0.07
4/25/81	4.8	1.94	0.12
4/30/81	8.0	1.98	0.12
5/01/81	4.8	1.97	0.11
5/02/81	8.0	1.69	0.16
5/04/81	14.5	2.09	0.05
5/07/81	8.0	2.10	0.05
5/08/81	4.8	1.84	0.10
5/10/81	8.0	2.12	0.28
5/14/81	14.5	1.89	0.05
7/26/81	14.5	2.04	0.05
7/29/81	8.0	2.02	0.07
7/30/81	4.8	1.83	0.15
8/01/81	8.0	2.10	0.31
8/01/81	14.5	2.15	0.04
8/06/81	8.0	2.05	0.17
8/07/81	4.8	2.01	0.08
8/08/81	4.8	2.01	0.08
8/11/81	8.0	2.01	0.07
8/12/81	8.0	2.19	0.06
8/14/81	4.8	1.91	0.12

is that 3C 371 is not a bright X-ray source and not highly variable. Previous observations of the region were probably confused with the star. (This suggests that the star may be an interesting object to study since it appears to be highly variable.)

An extrapolation of the ultraviolet spectrum falls below the X-ray data, although it may be in agreement with the X-ray flux density if the X-ray emission is in fact variable by a factor of a few.

III. SYNCHROTRON SELF-COMPTON MODEL FITTING

a) *Homogeneous Source Model*

Figure 2 is a composite plot of our observations of the core component of 3C 371. The relatively strong polarization and variability of the optical flux would favor a nonthermal origin for this radiation (see Angel and Stockman 1980). The simplest interpretation would assume that the radio to far-infrared data are part of a synchrotron component of slope $\alpha = 0.6$–0.7. This then breaks at $\nu_{max} \sim 5 \times 10^{14}$ Hz to a slope of $(4\alpha/3) + 1$, as a result of energy losses on a time scale which is short compared with that required for the electron pitch angles to become isotropic (Kardashev 1962). This synchrotron component must be self-absorbed at a frequency greater than $\sim 10^{11}$ Hz, so as not to exceed the lower frequency radio observations. This is particularly true for our August observations, for which the 10.1 μm measurement strongly suggests that α is closer to 0.7 than to 0.6. The X-ray data lie above an extrapolation of the *IUE* data and suggest a second component. (We cannot be absolutely certain of this since our X-ray observations are from earlier epochs.)

As argued by Worrall and Bruhweiler (1982), the observations do not reveal the frequency at which the synchrotron component is self-absorbed, ν_m, or the source size at the self-absorption frequency. Synchrotron self-Compton (SSC) model solutions depend strongly on these parameters. Radio maps of a particular source are made at frequencies which are almost certainly below the self-absorption frequency of that synchrotron component which produces the largest Compton contribution in the source. Incorporation of such observed sizes into the SSC formulae for BL Lac objects (e.g., Schwartz, Madejski, and Ku 1982) tends to give only lower limits to the amount of relativistic beaming required, rather than a tight constraint. Here we present a more complete treatment of the model fitting of Worrall and Bruhweiler (1982).

Our basic assumption is that no electron reacceleration occurs in the source. Therefore, we can apply the SSC equations in the form given by Marscher *et al.* (1979) and Marscher (1983). As shown by Worrall and Bruhweiler (1982), in the absence of relativistic beaming, the electron synchrotron lifetimes are always much less than the variability time scale of the source for all reasonable values of ν_m. This has also been shown to be the case for 3C 371 by Perley and Johnston (1979). Their calculations, using a specific value for ν_m, gave a synchrotron lifetime of ~ 3 days for electrons producing photons at ν_m, whereas the dimension of the source gave a light-travel time of ~ 6 months. Here we require that, for any predicted light crossing time of the source at ν_m, the electrons which produce synchrotron photons at an energy as high as ν_{max} can live precisely this long. In the usual notation, the Doppler factor, δ, is defined as $(1 - \beta^2)^{1/2}/(1 - \beta \cos \xi)$, where β is the bulk velocity in units of c, and ξ is the angle of relativistic motion relative to the line of sight. If we assume that the Compton flux density at 1 keV, F_C, amounts to 1 μJy, we find an acceptable value of ν_m for a δ between 10 and 35. A minimum can be set on the predicted variability time scale at ν_{max}, in the observer's frame, by selecting the largest allowed ν_m for a given δ. We find values of 100 hr for $\delta = 10$, and 0.3 hr for $\delta = 25$.

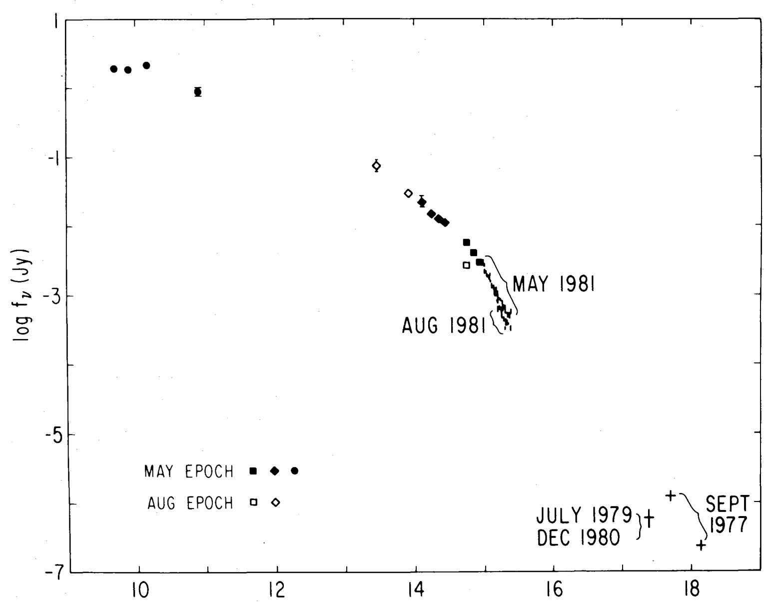

FIG. 2.—A composite spectrum of the core component of 3C 371, after correction for reddening. Data for the August epoch are only shown where fluxes differ significantly from the May observations or, in the case of the far-infrared measurements, where no May data are available. Radio, near-infrared, and visual data symbols are larger than the measurement errors. The 1979 July/1980 December X-ray data point is from the *Einstein Observatory* (this paper). The 1977 September X-ray data are from Marshall *et al.* (1979) and Snyder *et al.* (1982), and may include significant contributions from a nearby star (see § II*d*).

If F_C is only 0.1 μJy, then the lower limit to δ increases to 15, and the minimum variability time scale is 40 hr. Similarly, δ may be slightly reduced if a larger Compton flux density is permitted. The parameters of the solution for which $\delta = 10$, $\nu_m = 10^{11}$, and $F_C = 1$ μJy are given in Table 8. For these parameters it is found that the Compton luminosity of the source is equal to its synchrotron luminosity, and the electron lifetimes are at their maximum. The dependence of the relativistic particle energy density on δ, for a fixed Compton flux density contribution, is $\sim\delta^{12}$. Because of this strong dependence, it is noteworthy that values of δ near 10 give relativistic particle energy densities which are comparable to those of the magnetic field and synchrotron photons.

The observational inputs to our model are purely spectral, and thus the predicted constraints on temporal variability can be compared with observations. Correlated variability between different wave bands is expected, although the form this takes is difficult to predict. Small changes in the magnetic field strength, for example, can lead to variations in ν_{max}. This may be the reason for the constant infrared flux—and yet reduced visual and ultraviolet fluxes—between our May and August observations. It would be interesting to compare far-infrared flux, at frequencies below ν_{max}, with simultaneous X-ray data. However, full spectral coverage of the infrared to ultraviolet region would be required in order to determine ν_{max}, then to extrapolate the synchrotron contribution to the X-ray flux density, and finally to determine the residual Compton component as a function of far-infrared brightness. Our model parameters predict an observational variability time of $\sim$4 days at ν_{max} ($\sim 5 \times 10^{14}$ Hz). Small visual variations of about 0.1 mag have indeed been reported on time scales of one to a few days (Oke 1967; Sandage 1967), and there is at least one occurrence of the visual flux doubling over a 2 week interval (Pollock *et al.* 1979). For frequencies below ν_{max} the electrons can live longer—up to $\sim$10 months for ν_m. The X-ray band should exhibit variability correlated with that at ν_m. Our observations do indeed suggest less X-ray than optical variability. (We note that our present analysis of 3C 371 has a certain advantage over model fitting which uses the source variability time of a BL Lac object as an SSC model input parameter [e.g., Worrall *et al.* 1982; Bregman *et al.* 1984]. It is difficult to assess the uncertainty on this input parameter, which needs to be measured at ν_m and which in turn has a large impact on the derived δ. The shortest variability time scale is required in order to set any upper limit on δ.)

TABLE 8

3C 371 SSC Model Parameters ($H_0 = 50$ km s^{-1} Mpc^{-1}; $q_0 = 0$)

$z = 0.0506$
$\alpha = 0.7$
$\delta = 10$
$\nu_m = 10^{11}$ Hz (assumed synchrotron self-absorption frequency in observer's frame)
$\nu_{max} = 5 \times 10^{14}$ Hz (observed synchrotron break frequency)
$B = 0.14$ gauss (predicted rest frame magnetic field)
$\mu_B = \mu_\gamma = 7.8 \times 10^{-4}$ ergs cm^{-3} (predicted rest frame magnetic field and photon energy densities)
$\mu_e = 3.2 \times 10^{-5}$ ergs cm^{-3} (predicted rest frame electron energy density)
$t_v = 100$ hr (predicted source variability time, in observer's frame, for $\nu_m < \nu < \nu_{max}$, from predicted size at ν_m)
$t_a = 100$ hr (predicted apparent lifetime of electrons producing photons, observed at ν_{max}, by synchrotron and Compton radiation)
$t_s = t_C = t_a\delta/(1+z) = 1.3$ months (predicted synchrotron and Compton lifetimes of these electrons in the source frame)
$\theta = 0.026$ mas (predicted angular source size at ν_m)
$R = 10^{17}$ cm (predicted linear source size)

b) *The Königl Jet Model*

The homogeneous SSC model of the previous section does not explain radiation at frequencies below ν_m ($\sim$100 GHz). In particular, the relatively flat radio spectrum between 0.2 and 90 GHz is not accounted for. (See Kellermann and Pauliny-Toth 1969 and Owen, Spangler, and Cotton 1980 for a radio spectrum over a larger energy range than our measurements.) Königl (1981) shows that a flat radio spectrum can be achieved for a relativistic jet of Doppler factor δ and cone angle Φ, viewed at an angle ξ to its axis, and for which the magnetic field and electron density fall off as a function of distance from the apex, r (pc), by $B_1 r^{-m}$ and $K_1 r^{-n}$, respectively. The electrons are continuously accelerated with a power-law index of $(2\alpha_0 + 1)$, which is assumed constant along the jet. The observed flux density distribution from the radio to γ-ray bands depends on all of these parameters. We have applied this model to 3C 371 and fail to find a fit to the radio data, although the model may explain the observations above $\sim 10^{11}$ Hz.

Our spectral data of Figure 2 provide the input parameters for Königl's equations. Our first interpretation assumes that $\nu_{sb}(r_u)$, the synchrotron break frequency due to electron energy losses at the largest jet distance, r_u, is $\sim 5 \times 10^{14}$ Hz. The spectral slope immediately below this, α_{s2}, is $\sim$0.7, and the slope above is $\alpha_{s3} \geq 1.7$. Our millimeter data suggests a low-frequency slope of $\alpha_{s1} = 0.4$. The intersection of the power laws of indices α_{s1} and α_{s2} gives the self-absorption frequency of the lowest energy electrons at the smallest jet distances, r_m, as $\nu_{sm}(r_m) = 6.3 \times 10^{12}$ Hz. Proceeding by setting $\alpha_{s3} = 1.7$, we find $m = 1.31$, $n = 1.08$, and $\alpha_0 = 0.6$. If the 1 keV Compton-produced flux density is ≤ 1 μJy, then a solution of Königl's equations (5), (6), (12), and (13) gives

$$1.4 \times 10^{13} \leq \delta^{7.96}\Phi^{1.59}(\gamma\beta)^{3.18}(\sin\xi)^{-1} ,$$

where Φ is in degrees, and γ is the Lorentz factor $\gamma = (1-\beta^2)^{-1/2}$. If we approximate $\sin\xi = 1/\gamma(=1/\delta)$ so that the source orientation provides the full flux enhancement of the relativistic beaming, then, to satisfy $\Phi < \xi$, we find $\delta \geq 10$. If $\Phi \approx 4^\circ.1$, then $\xi \leq 5^\circ.7$, $B_1 \geq 1.2 \times 10^{-3}$ gauss, $K_1 \leq 2 \times 10^4$ cm^{-3}, $R_m \geq 3.2 \times 10^{-4}$ pc. (The inequalities apply for minimum δ, where the Compton contribution at 1 keV is less than 1 μJy.) Although the derived parameters are reasonable, the fit will not reach frequencies low enough for the observed radio flux. (This would also appear to be true for the application of this model to the BL Lac object 2155−304 by Urry and Mushotzky 1982.) For 3C 371, the minimum radio frequency is given by the self-absorption frequency of the highest energy electrons at the largest jet distance,

$$\nu_{sm}(r_u) = \nu_{sm}(r_m)[\nu_{sb}(r_u)/\nu_{sm}(r_m)]^{-c} ,$$

where $c = k_m/k_b$, and k_m and k_b are evaluated from m, n, and α_0 and equal 0.91 and 1.93, respectively. Thus, $\nu_{sm}(r_u) \approx 8 \times 10^{11}$ Hz, and no radiation at lower frequencies is explained by the model. It follows too that $r_u/r_m \approx 10$, and the angular size of the jet in the observer's frame is only $\sim 2 \times 10^{-4}$ mas at 8×10^{11} Hz. The electron cooling times imply variability on a time scale of ~ 1 hr at $\nu_{sm}(r_m) \approx 6.3 \times 10^{12}$ Hz and at the corresponding Compton component frequency of $\nu_{Cm}(r_m) \approx 10^{17}$ Hz, and on the time scale of ~ 10 hr at $\nu_{sb}(r_u) \approx 5 \times 10^{14}$ Hz. Observations may support an optical variability time scale this short (see § III*a*). The qualitative difference between 3C 371 and the example fit in Figure 2 of Königl's paper (in which the radio part of the spectrum *can* be modeled) is the greater degree of steepening at a lower frequency ($\sim 5 \times 10^{14}$ Hz) observed in 3C 371, meaning that $\nu_{sb}(r_u)$ is not very much larger than $\nu_{sm}(r_m)$.

For an alternative interpretation, we assume that the observed spectral break at 5×10^{14} Hz is the self-absorption frequency of the lowest energy electrons at the smallest jet distance, $\nu_{sm}(r_m)$. Our observations then constrain $\alpha_{s1} = 0.7$ and $\alpha_{s2} = 1.7$. Again, the model cannot explain the radio spectrum below 100 GHz, where $\alpha < 0.7$. Our previous interpretation found a modest value for δ, an inner jet size of $R_m \geq 32 R_{S8}$ (where R_{S8} is the Schwarzschild radius for a $10^8\ M_\odot$ black hole), and maximum values for the particle density and magnetic field at R_m of $\leq 10^8$ cm^{-3} and ≥ 45 gauss, respectively. The alternative interpretation, however, requires $\delta \geq 400$, $R_m \geq 1.7 R_{S8}$, and a particle density and magnetic field at R_m of $\leq 3 \times 10^{13}$ cm^{-3} and $\geq 3 \times 10^3$ gauss, respectively. Such a high particle density is probably two or three orders of magnitude above physical limits, but uncertainties are large enough that we can probably not rule out the assumptions of this interpretation. The fact that spectral breaks between the infrared and ultraviolet appear common in BL Lac objects (Worrall and Bruhweiler 1982) possibly suggests similar constraints on physical parameters throughout the class of objects. It would then seem more reasonable if this break were associated with conditions close to the compact core, $\nu_{sm}(r_m)$, rather than with energy losses farther along a jet, $\nu_{sb}(r_u)$.

VLA radio observations at 1.5 and 5 GHz have shown 3C 371 to be of the core type, with one-sided secondary emission $\sim 3''.3$ away (Perley and Johnston 1979). Perley, Fomalont, and Johnston (1980) suggest that the object fits into a class of normal double-lobed radio sources which are viewed nearly along the lobe axis, such that relativistic effects enhance both the core radiation and that of the approaching jet. A relativistic Doppler factor of the size we derive here for a small inner core component would brighten the core and approaching secondary component sufficiently to overwhelm emission from the radio lobes, which may be present at a level below current detection sensitivity. More recently, Pearson and Readhead (1981), using VLBI at 5 GHz, have resolved a component which is ~ 4.5 mas from the core and at a position angle which is close to, but significantly different from (8°), the larger scale size secondary emission. However, the authors do not discount the possibility that both the mas and arcsec features are part of the same continuous "jet." If β_{obs} is the apparent velocity relative to that of light, for $z = 0.0506$ ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$), the observed separation of components will be $0.23\beta_{obs}$ mas yr^{-1}. Since $\delta = (1 - \beta_{obs}^2 + 2\beta_{obs} \cot \xi)^{1/2}$ (Blandford and Königl 1979), $\beta_{obs} \approx \delta$ for $\sin \xi = 1/\gamma (= 1/\delta)$. If $\delta \geq 10$, the separation of ≥ 2.3 mas yr^{-1} is relatively large and may be detectable.

IV. LINE RADIATION

a) Emission Lines

The optical spectrum presented by Miller (1975) contains several emission lines in addition to the stellar absorption features which are characteristic of an elliptical galaxy. Miller demonstrates that, if a power-law continuum is subtracted from his data, the remaining spectrum is similar to that of the elliptical galaxy NGC 1052. Miller then suggests that the shock-heating model, used to explain the emission lines in NGC 1052 (Fosbury *et al.* 1978), is applicable to 3C 371. However, the intense visual power-law continuum in 3C 371 suggests a difference between the two objects. And now, our *IUE* measurements, together with the known X-ray flux, reveal the presence of a potentially strong source of ionizing radiation.

The visual emission-line fluxes are given by Miller, French, and Hawley (1978) to $\sim 50\%$ accuracy. The ratio of our *IUE* Lyα flux to their Hβ flux is roughly 63. This is within the predicted range for narrow-line region (NLR) gas in active galaxies (Netzer 1982), but it seems to be discrepant with the low values of less than 10 which are usually observed from the broad-line region (BLR) gas in QSOs and Seyfert 1 galaxies. The difference may be due to the absence of BLRs in 3C 371. The strongest visual lines are [O III] and [O II], characteristic of the NLR gas in QSOs and Seyfert galaxies. In the Miller (1975) data, Hβ was too weak to search for line broadening, and Hα sat on the atmospheric B band, rendering even a flux determination difficult. Our Lyα emission (Fig. 1) appears to be slightly broadened, particularly to the red. The apparent width of the line in our August data is a little less, and we estimate a velocity broadening of $\leq 1.5 \times 10^3$ km s^{-1}. Assuming no BLR gas, the asymmetry could result from radial infall of the clouds if the clouds between the compact core and the observer are more brightly illuminated by a relativistically beamed core than those on the far side.

It is interesting to compare line ratios of Lyα:[O II]:Hβ:[O III]:[O I] observed in 3C 371, i.e., 63:5:1:11:3, with values predicted in the NLR of NGC 4151 by Ferland and Mushotzky (1982), using an ionization model, solar abundances, and before correcting for the high NGC 4151 reddening, i.e., 82:2:1:17:1. The only qualitative difference, given the 30%–50% uncertainties in the 3C 371 line measurements, is that 3C 371 is stronger in its [O II] and [O I] lines. This is a feature which can be explained in a shock-heated galaxy model. However, Ferland and Mushotzky (1982) have found that the strengths of these lines relative to the higher ionization lines are dependent only on the cloud thickness as long as there is energy in hard X-rays to provide an ionization source deep into the clouds.

Shuder (1981) shows that 3C 371 does not fit the good correlation between Hα flux and visual continuum luminosity found for a sample of QSOs and Seyfert galaxies. The continuum is roughly two orders of magnitude too bright for the line emission. Since an Hβ flux is also measured for 3C 371, we can use Yee (1980) to confirm the discrepancy for this line also. The relativistic beaming of the optical to X-ray continuum may provide an explanation for this. Only those clouds in a solid angle of $\sim \delta^{-2} \leq 0.01$ sr will be radiated by an ionizing luminosity as bright as that which we observe. Clouds not in the beam will see an ionizing luminosity reduced by a factor as large as δ^4.

b) Absorption Lines

Although we cannot be absolutely confident in our absorption-line measurements (§ II*a*), particularly the N V measurement, we will briefly discuss implications concerning the nature of the absorbing gas, assuming the reality of the lines.

Assuming that the measurements fall on the linear part of the curve of growth, and using the transition probabilities of Morton and Smith (1973), our equivalent-width measurements imply that $N_{(\mathrm{C\,IV})} > 7.6 \times 10^{14}$ atoms cm^{-2} and $N_{(\mathrm{N\,V})} > 2.7 \times 10^{14}$ atoms cm^{-2}. The absorber could lie in the core of 3C 371 or be associated with the elliptical galaxy. The redshift of the lines rules out association with intervening gas which is remote from the source. The lower limits to the C IV and N V column densities are close to values predicted for the NLR of NGC 4151 by Ferland and Mushotzky (1982). However, using the NLR column densities in Table 2 of Ferland and Mushotzky (1982), we predict that we should measure equivalent widths which are at least 10 times the C IV value for Si II (λ1264), O I (λ1304), and C II (λ1334), and we would expect a very large absorption at Lyα. Nonsolar abundances could cause some discrepancy between observations and predictions, but the lack of strong C II (λ1334) absorption is difficult to explain away.

If the gas is collisionally ionized, inspection of the steady state ionization curves of Shapiro and Moore (1976) suggests that the absorber has a temperature $\sim 3 \times 10^5$ K. An appreciable Si IV (λ1394) absorption would be seen if the temperature were lower. The measurements of Ulrich *et al.* (1980) suggest that the gas in our own galactic halo, if collisionally ionized, may have similar column densities of C IV and N V to those in 3C 371 and may be of only slightly lower temperature.

One cannot rule out the possibility that the tentatively identified C IV and N V features in 3C 371 are produced by photoionization. The ionization is quite similar to that observed in the winds of galactic O stars. Here, photoionization from the stellar continuum and Auger ionization by X-rays have been suggested as ways of providing the observed C IV and N V (Cassinelli, Castor, and Lamers 1978; Cassinelli and Olson 1979). A similar process may give rise to features of these ions in 3C 371.

V. SUMMARY

1. We have coordinated measurements of 3C 371 at a broad range of wave bands from the radio to the ultraviolet, at two epochs separated by 3 months. Whereas the radio and infrared fluxes were unchanged between the two epochs, the visual and ultraviolet fluxes decreased by $\sim 35\%$. We have also presented new X-ray flux measurements obtained with the *Einstein Observatory*.

2. The multifrequency measurements show spectral steepening at visual frequencies. An extrapolation of the ultraviolet spectrum falls below the X-ray data.

3. We have assumed that the infrared to ultraviolet continuum is produced by synchrotron radiation. A homogeneous model in which the source has a bulk velocity βc toward the observer at a small angle to the line of sight, ξ, requires $\delta = (1 - \beta^2)^{1/2}/(1 - \beta \cos \xi) \geq 10$; otherwise the synchrotron self-Compton radiation will exceed the measured X-ray flux. High values for δ are also found when the data are fitted to the jet model of Königl (1981). Unfortunately, neither model incorporates the flux density at frequencies less than 100 GHz. This radiation must come from a larger external region. Indeed, 5 GHz radiation has already been partially resolved (Perley and Johnston 1979; Pearson and Readhead 1981).

4. We have discovered a Lyα emission line in both *IUE* spectra, at the same redshift as previously identified weak emission features. We favor gas recombination, after its photoionization by the ultraviolet to X-ray continuum radiation, as the means of production of these lines.

5. We tentatively identify absorption lines of C IV and N V in one of our *IUE* spectra, which might indicate the presence of a hot ($\sim 3 \times 10^5$ K) gaseous halo in 3C 371.

We thank Professor M. J. Rees and Dr. R. C. Puetter for enlightening discussions. Drs. P. LeVan, R. Puetter, and H. E. Smith are thanked for their assistance in the acquisition of the infrared data. We thank the *IUE* observatory staff for assistance in obtaining and reducing the *IUE* observations, particularly Dr. D. Klinglesmith for making available the Fahey-Klinglesmith software package. The *IUE* work was supported by NASA grant NAG 5-63, the Michigan radio astronomy by NSF grant AST 80-21250, the KPNO observations by the US Air Force Office of Scientific Research grant 81-0161, the Rosemary Hill Observatory measurements by NSF grant AST-8203926, the Caltech measurements by an NSF grant, and the *Einstein Observatory* work by NASA grant NAS-8-30753.

REFERENCES

Aller, H. D., Aller, M. F., and Hodge, P. E. 1981, *A.J.*, **86**, 325.
Angel, J. R. P., and Stockman, H. S. 1980, *Ann. Rev. Astr. Ap.*, **8**, 321.
Blandford, R. D., and Königl, A. 1979, *Ap. J.*, **232**, 34.
Bregman, J. N., *et al.* 1984, *Ap. J.*, **276**, 454.
Burstein, D., and Heiles, C. 1978, *Ap. J.*, **225**, 40.
Cassinelli, J. P., Castor, J. I., and Lamers, H. J. G. L. M. 1978, *Pub. A.S.P.*, **90**, 496.
Cassinelli, J. P., and Olson, G. L. 1979, *Ap. J.*, **229**, 304.
Ferland, G. J., and Mushotzky, R. F. 1982, *Ap. J.*, **262**, 564.
Fosbury, R. A. E., Mebold, U., Goss, W. M., and Dopita, M. A. 1978, *M.N.R.A.S.*, **183**, 549.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Hackney, R. L., Hackney, K. R. H., and Kondo, Y. 1982, in *Advances in Ultraviolet Astronomy: Four Years of IUE Research*, ed. Y. Kondo, J. M. Mead, and R. D. Chapman (NASA Pub. 2238), p. 335.
Kardashev, N. S. 1962, *Soviet Astr.—AJ*, **6**, 317.
Kellermann, K. I., and Pauliny-Toth, I. I. K. 1969, *Ap. J. (Letters)*, **155**, L71.
Königl, A. 1981, *Ap. J.*, **243**, 700.
Marscher, A. P. 1983, *Ap. J.*, **264**, 296.
Marscher, A. P., Marshall, F. E., Mushotzky, R. F., Dent, W. A., Balonek, T. J., and Hartman, M. F. 1979, *Ap. J.*, **233**, 498.
Marshall, F. E., Boldt, E. A., Holt, S. S., Mushotzky, R. F., Pravdo, S. H., Rothschild, R. E., and Serlemitsos, P. J. 1979, *Ap. J. Suppl.*, **40**, 657.
Miller, H. R. 1981, *IAU Cir.*, No. 3593.
Miller, J. S. 1975, *Ap. J. (Letters)*, **200**, L55.
Miller, J. S., French, H. B., and Hawley, S. A. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 312.
Morton, D. C., and Smith, W. H. 1973, *Ap. J. Suppl.*, **26**, 333.
Netzer, H. 1982, *M.N.R.A.S.*, **198**, 589.
Oke, J. B. 1967, *Ap. J. (Letters)*, **150**, L5.
———. 1978, *Ap. J. (Letters)*, **219**, L97.
Owen, F. N., Spangler, S. R., and Cotton, W. D. 1980, *A.J.*, **85**, 351.
Pearson, T. J., and Readhead, A. C. S. 1981, *Ap. J.*, **248**, 61.
Perley, R. A., Fomalont, E. B., and Johnston, K. J. 1980, *A.J.*, **85**, 649.
Perley, R. A., and Johnston, K. J. 1979, *A.J.*, **84**, 1247.
Pollock, J. T., Pica, A. J., Smith, A. G., Leacock, R. J., Edwards, P. L., and Scott, R. L. 1979, *A.J.*, **84**, 1658.
Sandage, A. 1966, *Ap. J.*, **145**, 1.

Sandage, A. 1967, *Ap. J. (Letters)*, **150**, L9.
———. 1973, *Ap. J.*, **180**, 687.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Schwartz, D. A., Madejski, G., and Ku, W. H.-M. 1982, in *IAU Symposium 97, Extragalactic Radio Sources*, ed. D. S. Heeschen and C. M. Wade (Dordrecht: Reidel), p. 383.
Shapiro, P. R., and Moore, R. T. 1976, *Ap. J.*, **207**, 460.
Shuder, J. M. 1981, *Ap. J.*, **244**, 12.
Snyder, W. A., Wood, K. S., Yentis, D. J., Meekins, J. F., Smathers, H. W., Byram, E. T., Chubb, T. A., and Friedman, H. 1982, *Ap. J.*, **259**, 38.
Ulich, B. L. 1981, *A.J.*, **86**, 1619.
Ulrich, M. H., *et al.* 1980, *M.N.R.A.S.*, **192**, 561.
Urry, C. M., and Mushotzky, R. F. 1982, *Ap. J.*, **253**, 38.
Worrall, D. M., *et al.* 1982, *Ap. J.*, **261**, 403.
Worrall, D. M., and Bruhweiler, F. C. 1982, in *Advances in Ultraviolet Astronomy: Four Years of IUE Research*, ed. Y. Kondo, J. M. Mead, and R. D. Chapman (NASA Pub. 2238), p. 181.
Yee, H. K. C. 1980, *Ap. J.*, **241**, 894.
Zamorani, G., *et al.* 1981, *Ap. J.*, **245**, 357.

H. D. ALLER, M. F. ALLER, and P. E. HODGE: 817 Dennison Building, Department of Astronomy, University of Michigan, Ann Arbor, MI 48109

F. C. BRUHWEILER: Code 685, NASA Goddard Space Flight Center, Greenbelt, MD 20771

W. H.-M. KU: Columbia Astrophysics Laboratory, Columbia University, 538 West 120th Street, New York, NY 10027

R. J. LEACOCK, A. J. PICA, J. T. POLLOCK, A. G. SMITH, and J. WEBB: Department of Astronomy, 211 Space Sciences Research Building, University of Florida, Gainesville, FL 32611

K. MATTHEWS, G. NEUGEBAUER, and T. SOIFER: Physics Department, 320-47, California Institute of Technology, Pasadena, CA 91125

H. R. MILLER: Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303

J. J. PUSCHELL: Titan Systems, Inc., La Jolla Gateway, 9191 Towne Center Drive, Suite 500, San Diego, CA 92122

R. J. RUDY: Steward Observatory, University of Arizona, Tucson, AZ 85721

D. M. WORRALL: Center for Astrophysics and Space Sciences, C-011, University of California at San Diego, La Jolla, CA 92093