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FURTHER JOINT X-RAY, INFRARED, AND RADIO OBSERVATIONS OF CYGNUS X-3

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ABSTRACT

Observations of Cygnus X-3 have been carried out at 2.5–7.5 keV, 2.2 μ, 8.1 GHz, and 2.7 GHz over a 2 week period. The X-ray data show the periodic structure which is typical of Cyg X-3. At times the X-ray and infrared measurements show very similar periodic structure, both in phase and in shape, while at other times the infrared data show no periodic variability. The radio fluxes were unusually low during the period of observation; both the daily average radio flux levels and the spectral index remained nearly constant.

Subject headings: infrared: sources — radio sources: variable — X-rays: sources

I. INTRODUCTION

Cygnus X-3, besides being an interesting X-ray source because of its 4.8 hour period, is a unique radio and infrared emitter (see review by Hjellming 1973). At radio wavelengths Cyg X-3 shows erratic, frequency-dependent behavior with outbursts up to 20,000 times its quiescent flux level and with no evidence for the 4.8 hour period. In the infrared it has sometimes shown (*a*) fluctuations with a 4.8 hour period, (*b*) outbursts on time scales both of minutes and hours, and (*c*) an absence of periodic fluctuations.

Simultaneous measurements over a range of frequencies are potentially important in clarifying the nature of Cyg X-3. Simultaneous X-ray and infrared observations were carried out in 1973 July (Becklin *et al.* 1973, henceforth Paper I), while combined X-ray, infrared, and radio observations, some simultaneous, were made in 1973 August (Becklin *et al.* 1974, henceforth Paper II). The present paper reports the results of more extensive joint radio, infrared, and X-ray observations which took place during 1974 September 14 through 1974 September 29.

II. OBSERVATIONS

The X-ray data were obtained with the *Copernicus* satellite as described in Paper I; they represent the flux from 2.5 to 7.5 keV and were taken with a time resolution of 1 minute. The infrared observations were made at the Mount Wilson 2.5 m telescope using the photometric system described in Papers I and II. The data of 1974 September 14–17 were obtained with a 2.0–2.4 μ bandpass filter. After that, in order to improve the signal to noise ratio, a filter extending from 1.5 to 2.4 μ was used, and the fluxes were adjusted to correspond to the 2.0–2.4 μ (2.2 μ) band. The conversion from the 1.5–2.4 μ fluxes to the equivalent fluxes at 2.2 μ was derived from occasional measurements using the narrow-band filter interspersed between measurements with the broad-band filter. Measurements were made with a 7″ aperture and a 25″ chopper spacing; care was taken to avoid contamination by nearby field stars. The sensitivity was monitored at least hourly by observing a star within ~4′ of Cyg X-3, and all data were corrected for extinction due to the Earth's atmosphere. Observations typically lasted 6 minutes.

Radio data were obtained with: (1) the NRAO interferometer at frequencies of 2.695 and 8.085 GHz and spacings of 2700, 1800, and 900 meters and (2) with the NRAO 36 foot (11 m) antenna operating with a cooled 80 GHz receiver. The 2.7 and 8.1 GHz measurements were made in two different modes. In one mode, used during the nights of 1974 September 14–15 and September 18–30, successive measurements 24 minutes in duration were obtained for as much as possible of the 11 hour observing slot. In the other mode, 5 minute samples were taken roughly 6 times a day during the periods 1974 September 7–14 and September 16–18. Because of the unusually and consistently low levels of the radio emission, the 30 s samples going into each 24 or 5 minute measurement were vectorially averaged together to derive flux densities from the resulting amplitudes. Most of the 80 GHz data taken were useless because of problems associated with using a new receiver for the first time, but the flux from the source was successfully measured on the nights of 1974 September 27–28 and September 28–29.

III. RESULTS

The data are presented in Figures 1–8. On each figure, the minima in the X-ray flux are marked using an X-ray period of 0.199682 days and an epoch set by the minimum at JD 2,441,279.968 as determined by

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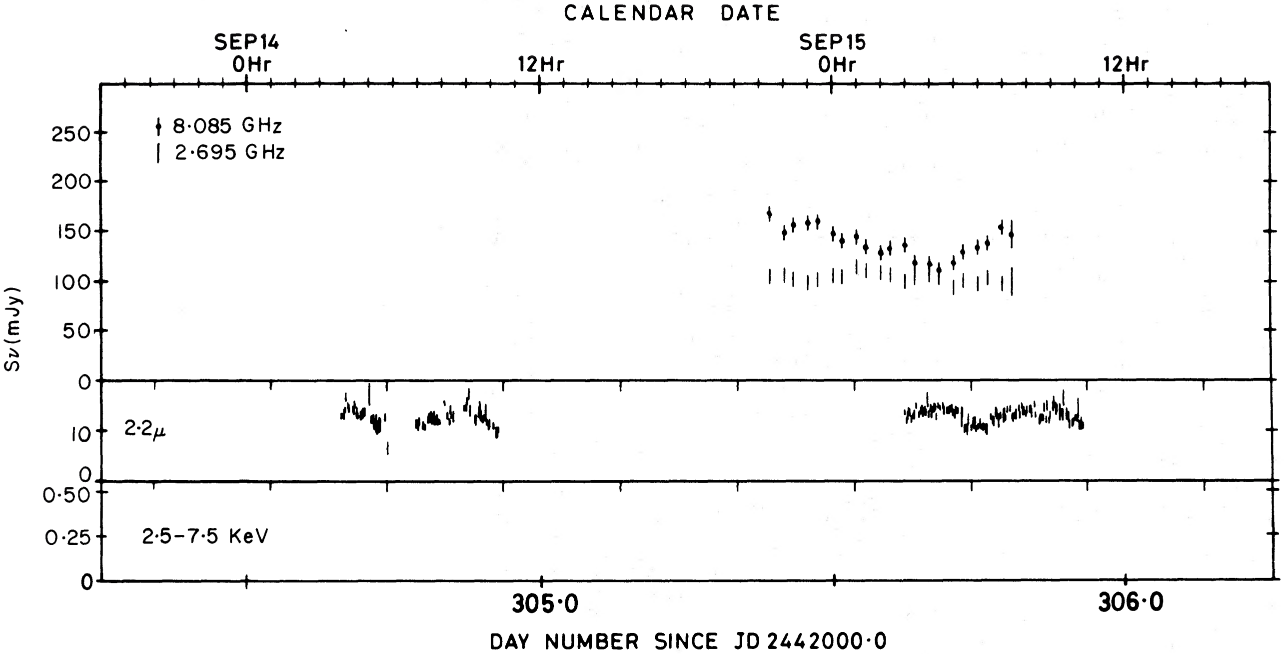

FIG. 1

FIGS. 1–8.—The X-ray, infrared, and radio data taken between UT 1974 September 14 and September 29 are presented. Earlier radio coverage extending from September 7 is not shown. Each X-ray data point represents three 1-minute integrations. The X-ray minima are marked on the central two abscissae.

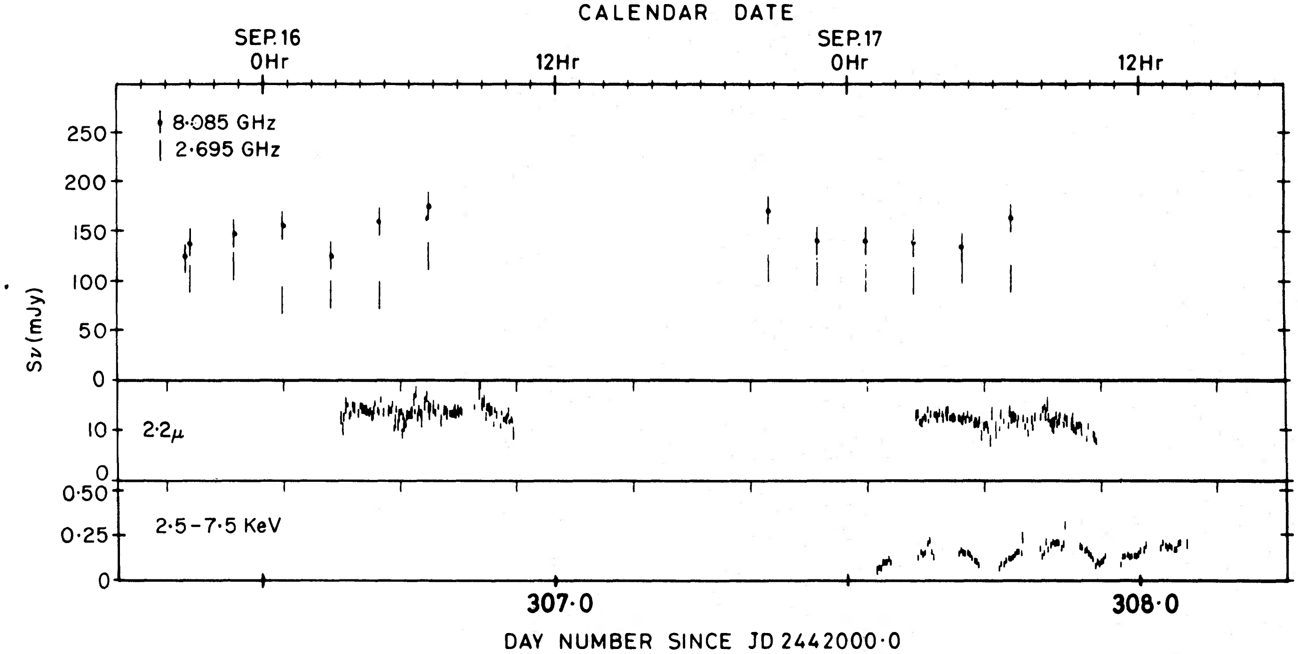

FIG. 2

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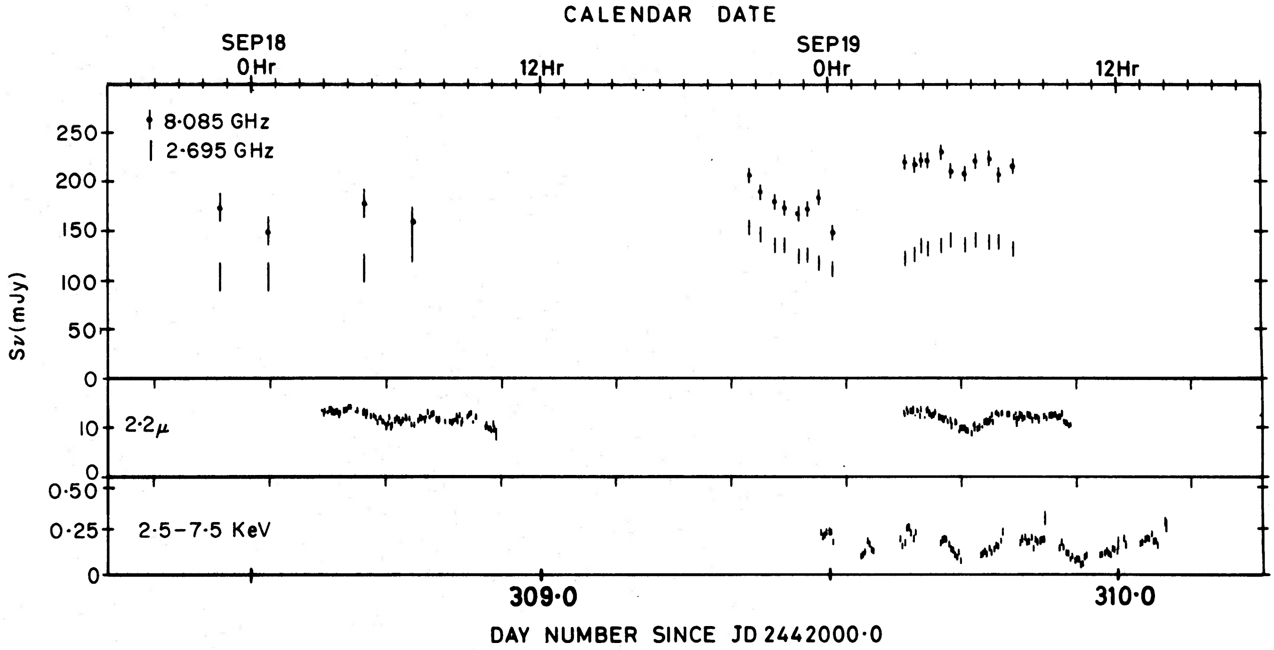

FIG. 3

Mason (1974). Both period and epoch agree with those determined by Leach *et al.* (1975); they differ slightly from those used in Papers I and II. The monotonic decrease in the infrared flux levels toward the end of some nights' observations may be an artifact of the fact that these data were taken through increasing amounts of atmosphere approaching 1.7 air masses. Although the data were corrected for atmospheric extinction and checks were made on a nearby comparison star and on BL Lac, whose infrared spectrum is very similar to that of Cyg X-3, there may be systematic errors related to the large air mass through color-sensitive effects of the refraction and degradation of seeing.

Figures 1–8 show that the infrared and radio emissions were in a quiescent state; no large outbursts such

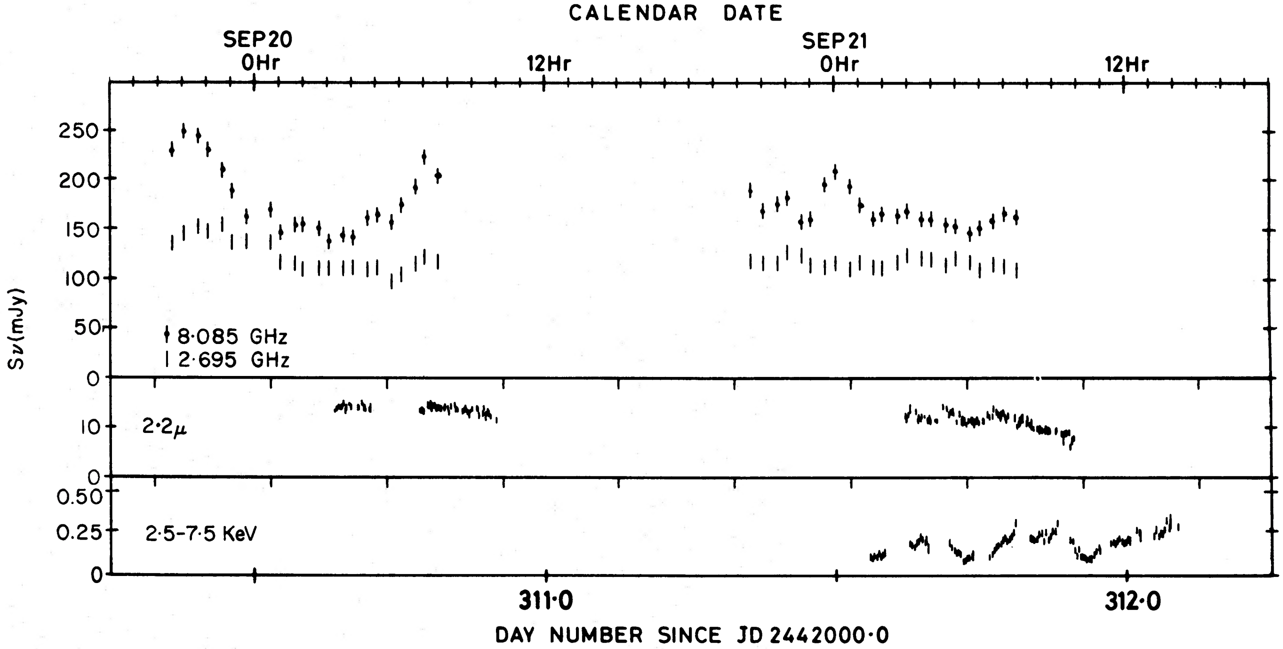

FIG. 4

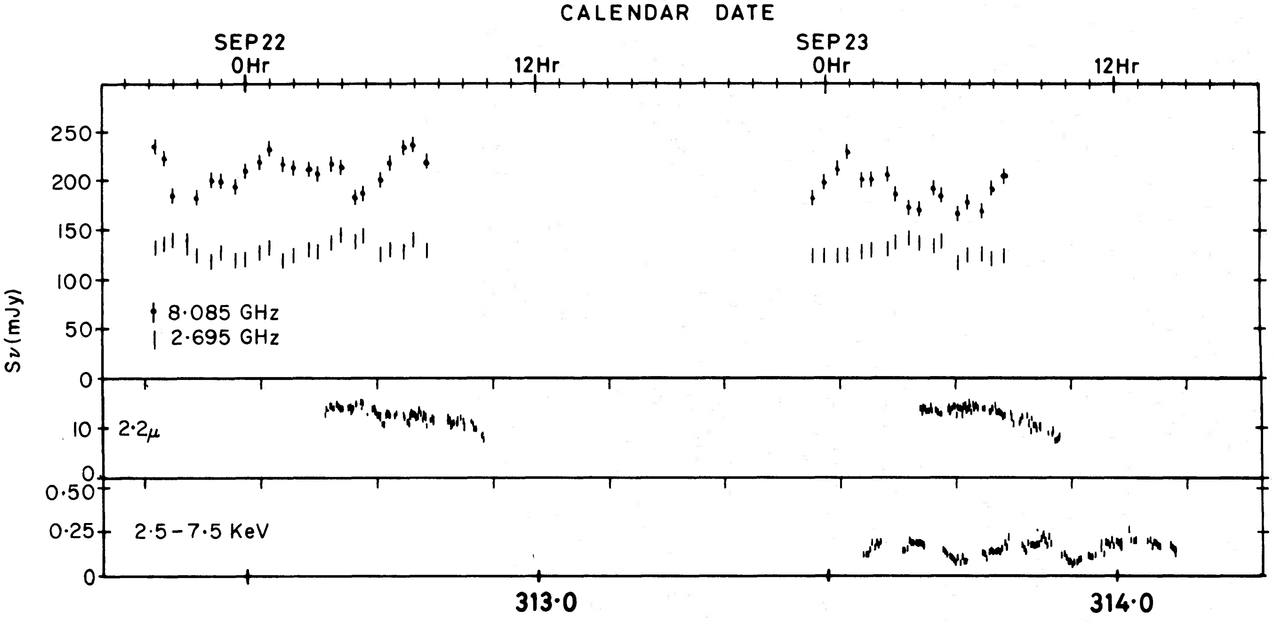

FIG. 5

as previously reported were seen over the entire time the source was observed. The luminosity ($=4\pi D^2\nu F_\nu$) of Cyg X-3 in this quiescent state was approximately 10^{30}, 10^{29}, 10^{25}, and 10^{24} W, respectively at 5 keV, 2.2 μ, 8.1 GHz, and 2.7 GHz, if Cyg X-3 is at a distance of 11 kpc (Lauque, Lequeux, and Rieu 1972). The infrared luminosity has been corrected to include 1.5 mag of extinction (Becklin *et al.* 1972).

The X-ray data show periodic behavior throughout, but the mean flux was at a relatively low level compared with previous *Copernicus* measurements (Papers I and II). The new X-ray data are shown folded modulo the 4.8 hour period in Figure 9 together with an average X-ray light curve of Cygnus X-3 derived by folding together all previous *Copernicus* observations of the source. The latter span a 2 year interval

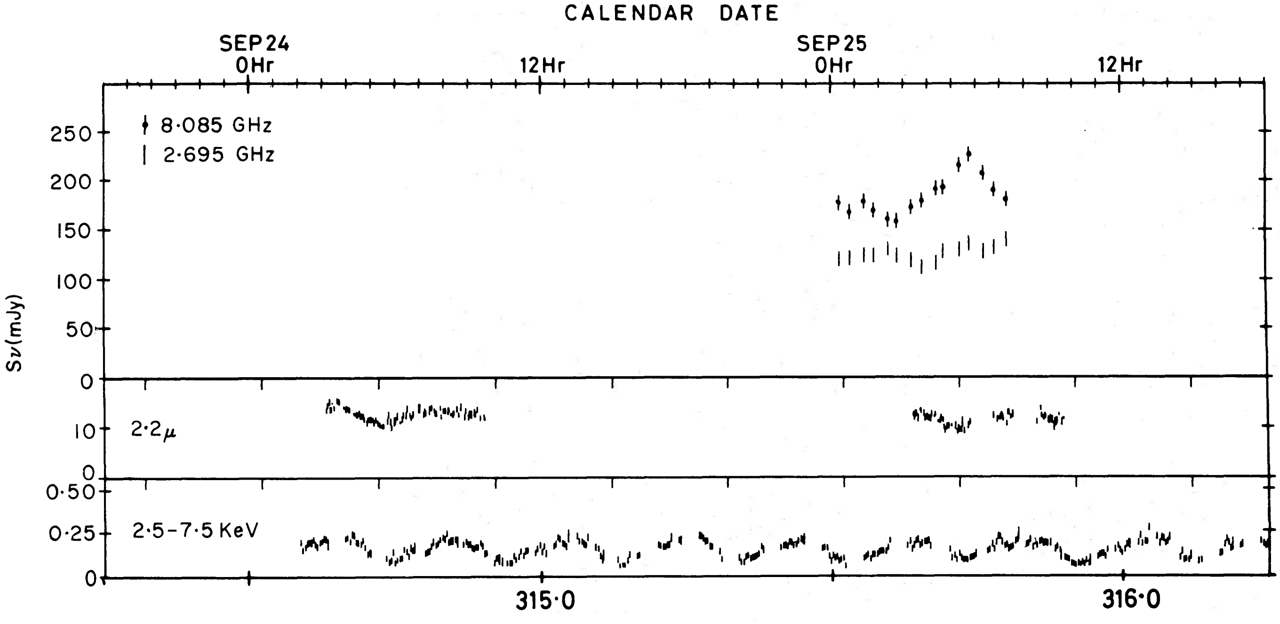

FIG. 6

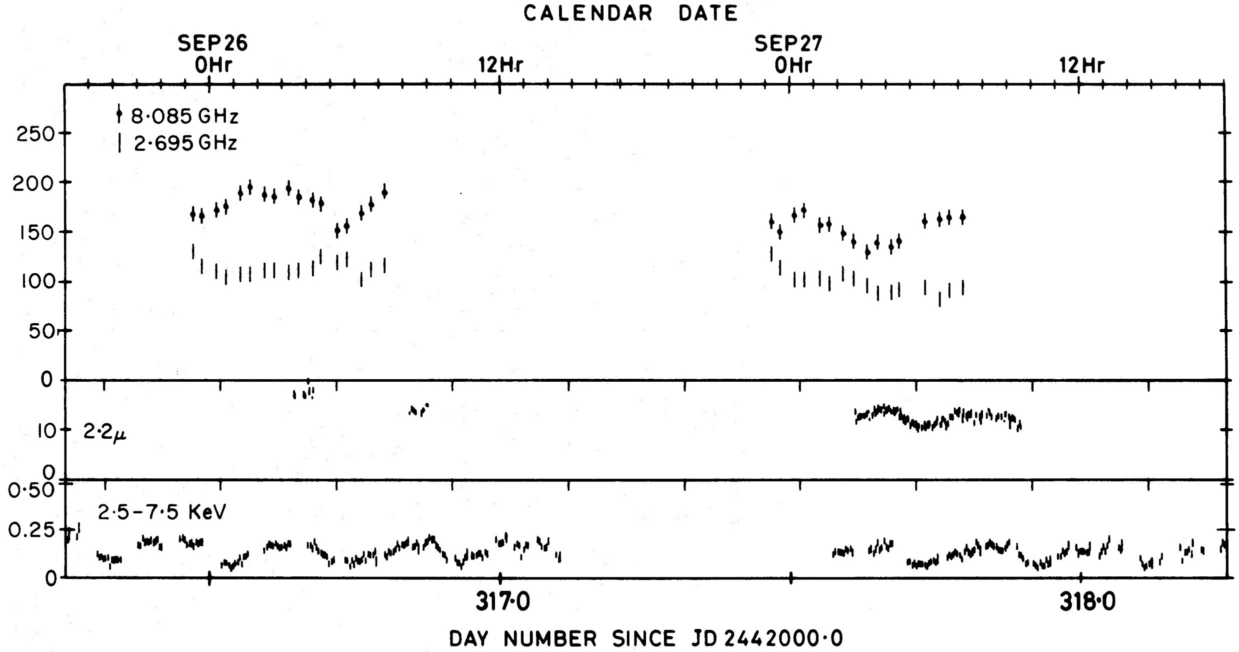

FIG. 7

and have been scaled, before folding, to the flux level between phases 0.4 and 0.8 of the cycle, measuring phase from the minimum. In this phase interval the flux level is relatively constant, and the procedure satisfactorily circumvents the problems which would otherwise arise when combining curves with different overall flux levels and different patterns of data coverage.

Although no large outbursts occurred in the infrared, it is clear that a variety of behaviors are present. On at least three days (1974 September 19, 24, and 27) the data showed the 4.8 hour modulation very clearly, and some remnant of this periodic structure is apparent in most of the observations. A detailed comparison of the X-ray and infrared light curves during these three days is shown in Figure 10. It is seen that both wave

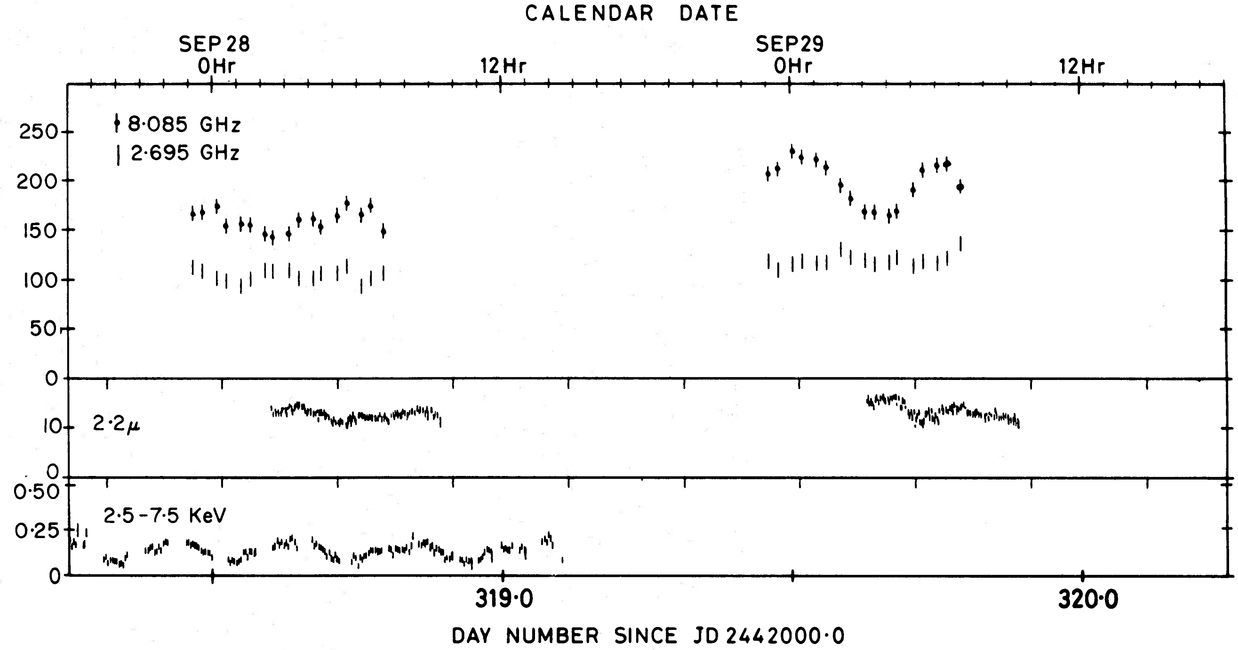

FIG. 8

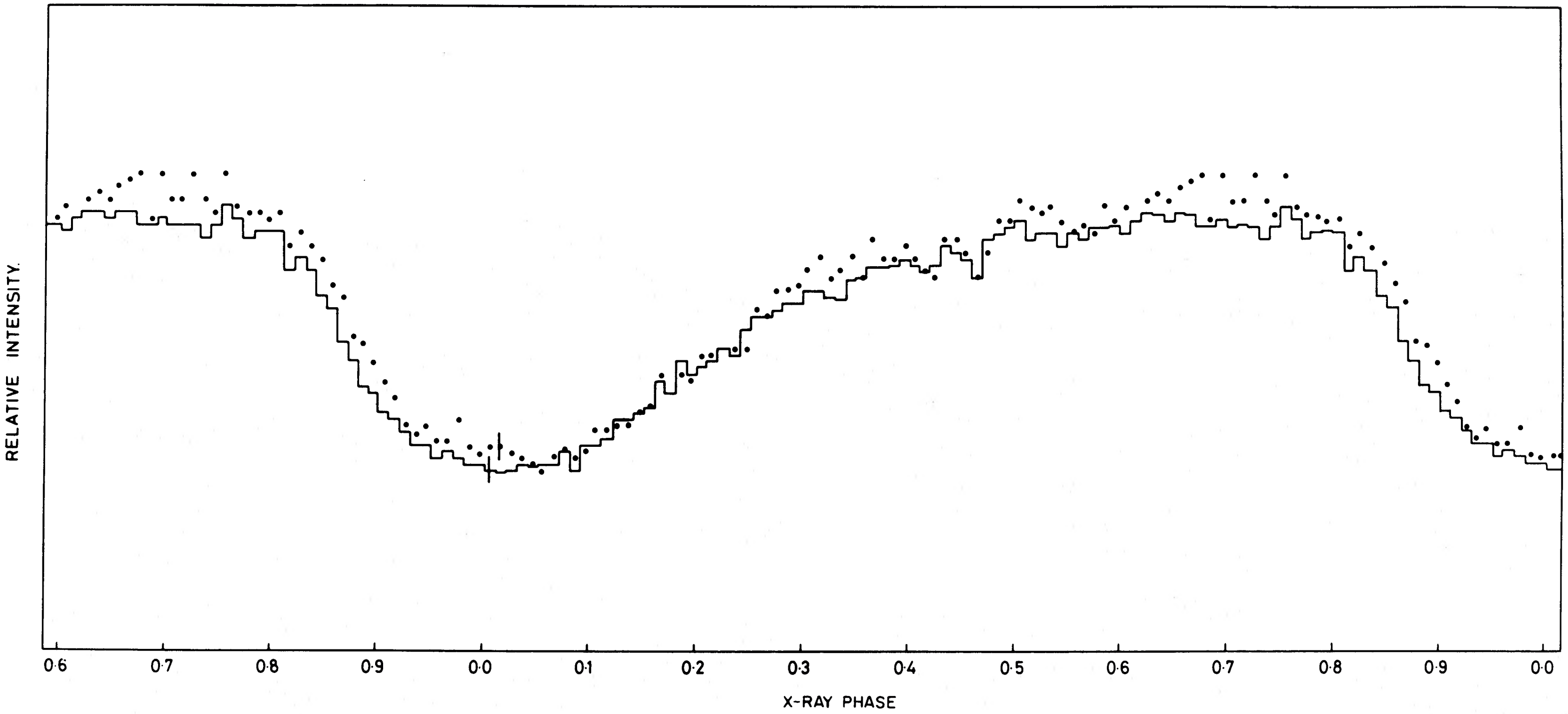

FIG. 9.—The X-ray data taken during 1974 September (*dots*) and the data from previous *Copernicus* observations of Cygnus X-3 (*histogram*) are folded modulo the 4.8 hour period. The data have been scaled to the flux level between phases 0.4 and 0.8, prior to folding. The error bars shown near zero phase are typical 1 σ errors. The ordinate scale is in arbitrary units with zero at the bottom.

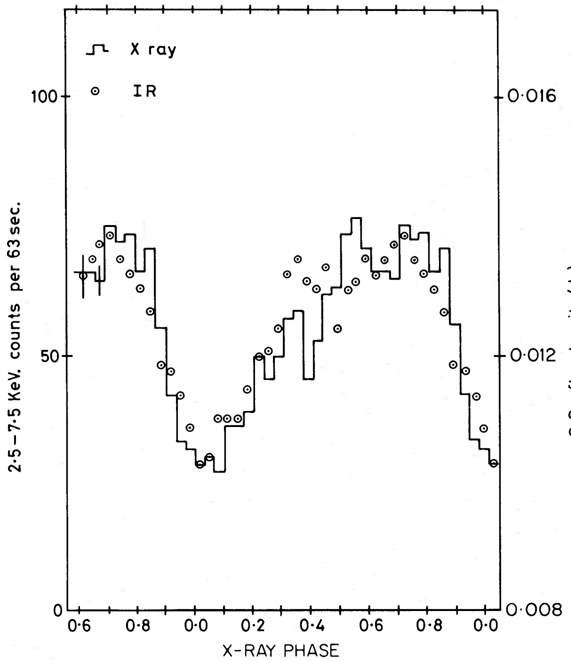

FIG. 10.—The three infrared cycles showing the most pronounced modulation are folded on the X-ray period and compared with the corresponding X-ray data. The data have been scaled to the same amplitude in the modulations, and 0.008 Jy has been subtracted from the infrared data. The error bars shown are 1 σ errors and are typical of all the data.

forms have the same overall shape, consisting of a slow rise followed by a sharp decrease. This shape is typical of both the average light curve during the present set of observations and the average curve obtained by folding together all *Copernicus* data on Cyg X-3, as evidenced by Figure 9. The phases of the light curves in the two frequency bands, as measured from the relatively sharp fall time, are the same to within an uncertainty of 0.03 of the period.

During the 1974 September run, when the mean flux level was 0.013 Jy, the maximum percentage modulation seen in the infrared was 30 percent. This is the same percentage as the modulation observed in 1973 July and in 1973 June, when the mean 2.2 μ flux densities were 0.014 Jy and 0.028 Jy, respectively.

Although periodic variations were commonly present, it is significant that the infrared data obtained on 1974 September 22 and 23 showed no 4.8 hour variations. Simultaneous X-ray data were obtained only on the latter of these days; during this time the X-ray emission showed normal periodic behavior.

Although an absence of the periodic fluctuations in the infrared data had been noted in Paper II, the uniqueness of the event made it impossible to determine whether its cause was a chance occurrence or a more regular modulation of the basic periodic component. The present data, which are characterized by a uniform low level periodic behavior and little or no discernible flaring, were subjected to a power spectrum analysis described below. The spectral resolution of the data is 1/15 cycles per day, and no significant broadening of the 5.01 cycle per day peak with a bandwidth larger than ~0.13 cycles per day was observed; also no significant side bands were present. This indicates that the 5.01 cycle-per-day carrier frequency did not have a large amount of amplitude modulation in any narrow frequency range above 0.13 cycles per day. In fact, the power spectrum of the noise in all the data sets (X-ray, infrared, and radio) was more typical of shot noise with a characteristic time scale of the order of 0.4 days.

The above analysis suggests that the observed change in the structure of the periodic component evident in the present data is caused by some randomly occurring event. Two obvious phenomena which could produce such behavior would be the random filling in of the flux at minimum, or the random modulation over a wide frequency band of the amplitude of the 4.8 hour variations. The former could be produced by flares, especially if they were to occur preferentially at minimum, while the latter could be produced by random obscuration of the region producing the variable flux. The present data cannot be used to distinguish between such models, but they do strengthen the fact that during some periods of time there is an absence of periodic fluctuations at infrared wavelengths.

The most remarkable characteristic of the Cyg X-3 radio source during the period 1974 September 7030 is the constancy of the source both in flux and spectral index. Figure 11 shows the relationship between the daily average flux densities at 2.7 and 8.1 GHz and the spectral index,

$$\alpha_{2695}{}^{8085} = \log(S_{8085}/S_{2695})/\log(8085/2695)\,.$$

A calculation on individual data integrations at the two radio frequencies (Figs. 1–8) yields a correlation coefficient of 0.75 corrected for observational uncertainties, with a probability of 10^{-5} that this could arise

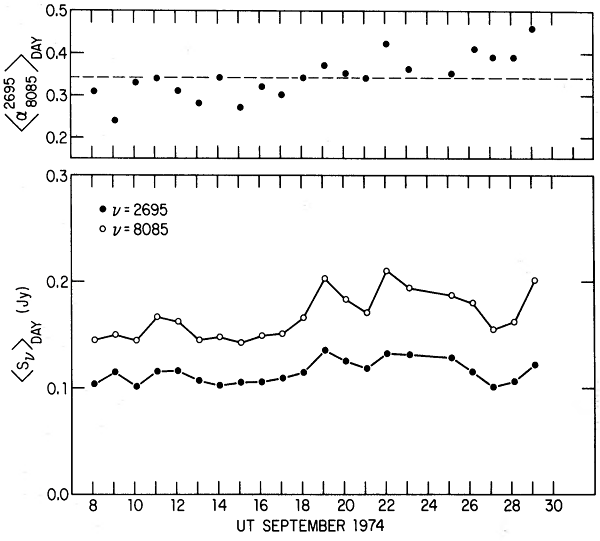

FIG. 11.—The average daily flux densities at 8.1 and 2.7 GHz and the radio spectral index are shown for the period of observation.

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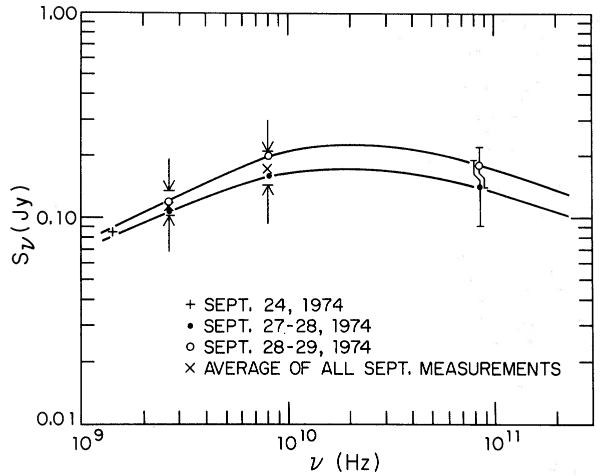

FIG. 12.—The form of the radio spectrum is shown obtained from the average daily fluxes at 80, 8.1, and 2.7 GHz. The point at 1.4 GHz was obtained by Braes *et al.* (1974).

by random fluctuations. Thus, the average radio flux densities and spectral indices for individual days are clearly not independent of each other, and between 1974 September 7 and September 30 the spectral index evolved from 0.3 to 0.45. This would not occur if the radio source consisted of completely independent flares with completely independent physical parameters —a hypothesis that might have been entertained because of the real variability that occurred on each and every day.

In Figure 12 the form of the Cyg X-3 radio spectrum is shown. A single measurement (Braes *et al.* 1974) with the Westerbork array at 1414 MHz on 1974 September 24 is shown together with average daily fluxes at 80, 8.1, and 2.7 GHz on the nights of 1974 September 27–28 and September 28–29. Also shown are the averages for the month of all measurements at each frequency and the maximum and minimum flux values attained at 8.1 GHz and 2.7 GHz. The spectrum for Cyg X-3 during the quiet levels found in 1974 September was remarkably stable, irrespective of hour-to-hour or day-to-day variations, compared with spectra obtained earlier during active periods (Hjellming 1973).

The average X-ray, infrared, and radio fluxes during each 4.8 hour cycle of the 1974 September observing period are plotted in Figure 13. Only X-ray data lying between phases 0.4 and 0.8 have been included in order to eliminate spurious intensity changes caused by differences in coverage, but the plot is insensitive to changes in the phase interval used. No phase selection has been made on the infrared and radio data. As mentioned above, the 8.1 and 2.7 GHz data show some correlation, but there is no convincing evidence from these data that the flux levels in the X-ray and infrared wave bands show any correlation with the radio fluxes on the time scales measured, or that the X-ray and infrared flux levels are correlated except in the 4.8 hour periodicity.

TABLE 1

POWER SPECTRUM OF INTENSITY VARIATIONS IN CYGNUS X-3*

Frequency	$\lesssim 1$	5.01	10.02	> 10 Cycles per Day
2.7 GHz......	0.11	< 0.03	< 0.02	0.01
8.1 GHz......	0.16	< 0.05	< 0.05	0.04
2.2 μ.........	0.04	0.10:	0.05:	0.03
2.5–7.5 keV....	0.06	0.38	0.10	0.03

* The power at a given frequency is expressed as the amplitude of an equivalent sine-wave modulation at that frequency. At 5.01 and 10.02 cycles per day (the 4.8 hr period and its first harmonic) this is the average amplitude (peak-to-mean) of the oscillation as a fraction of the mean flux. At lower and higher frequencies the table entries are the average spectral density in units of peak-to-mean amplitude (as a fraction of mean flux) per cycle per day. The spectral density has been corrected for observational error. As explained in the text, there is difficulty in separating the fundamental and harmonic in the power spectrum of the infrared data.

The data at each wavelength have been subjected to a power spectrum analysis; the results are summarized in Table 1. The discontinuities in the data sampling result in a power spectrum which is a convolution of the true power spectrum with the sampling spectrum, giving in some cases a very complex pattern. It is thus necessary to compute the window spectrum at each frequency, and any periodicity in the source will appear as a series of peaks corresponding to the window pattern (Gray and Desikachary 1973). The data were searched for periods from 0.075 days upward. The only significant peaks in the X-ray and infrared power spectra are those corresponding to a 4.8 hour modulation and its harmonics. The infrared power spectrum is very complex, however, since 4.8 hours is an almost exact submultiple of a day and the data were taken at daily intervals. Neither the 8.1 nor the 2.7 GHz data show significant power with a period of 4.8 hours. The higher upper limit at 8.1 GHz (Table 1) reflects the greater noisiness of those data; this increased noise is apparent in Figures 1–8 and is intrinsic to the source. There is some evidence for an 18 percent modulation of period 1.1 days in the 2.7 GHz data, appearing as a fundamental and twoside bands due to the sampling window, but the observations are too limited to be able to say that this is a true periodicity and not a quasi-periodicity in the fluctuations having approximately a 1 day time scale. There is no evidence for a 1.1 day modulation at 8.1 GHz.

IV. DISCUSSION

There are several theoretical models for Cyg X-3. Treves (1973) argues that the 4.8 hour period might be due to the precession of a rotating neutron star. Pringle (1974) attributes the X-ray emission to a neutron star revolving about a large star in a close binary system. In his model the X-ray variations are a manifestation of the different relative orientations of the X-ray source and the stellar wind while the infrared is free-free emission. Davidsen and Ostriker (1974) have an essentially similar model except that the X-ray source is a white dwarf. Basko, Sunyaev, and Titarchuk

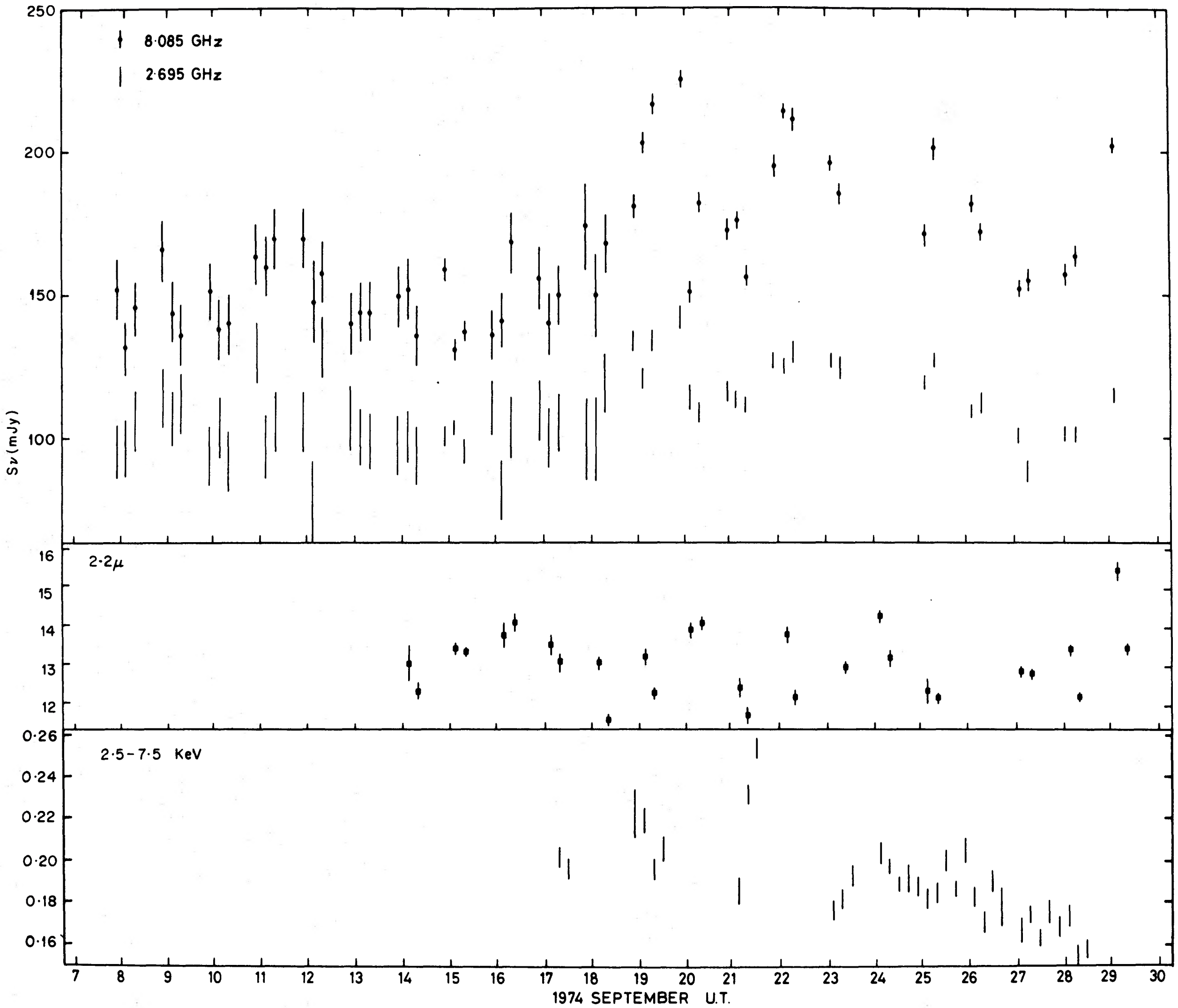

FIG. 13.—Average flux densities in the X-ray, infrared, and radio wave bands per 4.8 hour cycle of Cygnus X-3 during 1974 September are shown. In the case of the X-ray data, only data from phases 0.4 to 0.8 of each cycle have been used, so the plotted points represent the maximum flux per cycle.

(1974) propose a conceptually different model wherein the observed X-rays are those reflected off the large companion star.

Unfortunately, the present data do not serve to distinguish among the above proposals. In its simplest form, no model accounts for either the sometimes very exact duplication of the X-ray light curve by the infrared or the apparent absence of an infrared modulation at other times. Both of these aspects of the flux from Cygnus X-3 are established by the present data, and they must be explained by any satisfactory theoretical model for the source.

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