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RADIO FLUX DENSITY VARIATIONS OF CYGNUS X-3

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ABSTRACT

Variations in the flux density from Cyg X-3 are reported for the period 1982 October through 1985 March at 11 and 3.7 cm. Large flaring events (>1 Jy) occurred in 1982 September–October, 1983 February, 1983 September–October, 1984 September, and 1985 February–March. Since 1972, Cyg X-3 has displayed 15 known large flaring events. Six of these events have taken place during the months of September and October. These radio flaring events are probably due to a variable accretion rate onto the collapsed star of the binary system. Based on this small sample of data, there is a possibility of a 120 day periodicity in these large flaring events. This may be due to the presence of a third body in the Cyg X-3 binary system which modulates the accretion rate.

The recent spectacular event in 1983 September–October was also monitored at 6 cm. During this time the flux density varied on time scales of minutes to hours, with random variations at the 100 mJy level. A large flare began on September 30. The spectral index indicated a plasma that initially was optically thick but eventually became optically thin. This flaring event was similar to those of 1972 and 1982. From the detailed analysis of the 6 cm data, there appears to be no evidence of periodicity of order 4.8 hr in the radio emission with amplitudes greater than 50 mJy.

Subject headings: radio sources: variable — stars: radio radiation — X-rays: binaries

I. INTRODUCTION

A large radio outburst occurred in 1982 September for the binary Cyg X-3 (Geldzahler *et al.* 1983). This outburst happened 10 yr after the discovery of another large outburst (Gregory *et al.* 1972). During the 1982 outburst, the size of the radio emission as measured on two epochs appeared to expand at 0".01 per day along a position angle of 0°. Cygnus X-3 probably emits plasma along a precessing beam from a central object at speeds of order 0.3 c, similar to SS 433 (Hjellming and Johnston 1981).

Shortly after the 1982 September outburst, a program was undertaken with the Green Bank interferometer to search for large flaring events to study their spatial structure. A large flaring event was observed in 1983 September–October. Flux density measurements at 6 cm were also made during this period. The monitoring measurements from 1982 September to 1985 March and the detailed measurements of the 1983 flare are reported here. These long-term measurements should be helpful in searching for correlations between the radiation at other frequencies. Cygnus X-3 has a well-defined 4.8 hr period for the binary system with correlations in X-ray (Brinkman *et al.* 1972), IR (Becklin *et al.* 1973), possibly radio (Molnar, Reid, and Grindlay 1984; 1985) and muon (Marshak *et al.* 1985) emission. There are variations in the X-ray emission which have periods of 16.75, 18.7, and 34.1 days (Holt *et al.* 1976, 1979; Molteni *et al.* 1980; Bonnet-Bidaud and van der Klis 1981). A peak in the temperature of the X-rays was found during the 1972 radio outburst (Leach *et al.* 1975).

II. OBSERVATIONS

The objective of the monitoring campaign was to find the precursor to a large flaring event and then initiate detailed observations with a number of instruments. It was decided that if a flare greater than 3 Jy were observed, then the detailed program would be initiated. This happened in 1983 September and the results of this program are described in Spencer *et al.* (1986).

The Green Bank interferometer monitored the flux density at 11.1 and 3.7 cm three times a day. These measurements were in right circular polarization through 1983. Because of instrumental problems, the data since 1984 January 1 were in left circular polarization. Each observation was of 10 minutes duration. The two wavelengths alternated during this 10 minutes every other 30 s. The observations were calibrated using 3C 286 whose flux density was assumed to be 10.5 and 5.3 Jy at 11.1 and 3.7 cm, respectively. The typical uncertainty in the flux densities is 40 mJy for a five-minute integration. The Green Bank program is continuing.

For the large flaring event of 1983 September–October, measurements were made with the Jodrell Bank MERLIN interferometer, the Cambridge 5 km telescope, and the VLA[1].

Measurements were begun with MERLIN shortly after the start of the 1983 September radio activity. The observations reported here are those between the MK 2, a 25 m × 36 m parabolic antenna, and the 25 m Tabley antenna at 4995 MHz. The typical rms noise was 30 mJy after 10 minutes integration. Ten-minute integrations were used in the following analysis. Daily measurements of 3C 84 (assumed flux density 58.7 Jy) were used to calibrate the data.

The Cambridge 5 km telescope monitored the flux density from 27 September through 1983 October 31. These data were obtained at 11.1 cm using all eight antennas. The observations, of Stokes' parameters *I*–*Q*, were between 30 minutes and 12 hr in duration and were calibrated using either 3C 48 or 3C 286 (assumed flux density 9.21 and 10.53 Jy, respectively). The noise after one-hour integration was 5 mJy.

The VLA was used to monitor occasionally the flux density at 20, 6, 2, and 1.3 cm. These measurements were typically 10 minutes in duration of Cyg X-3 followed by a five-minute observation of the calibrator 2005+403 at all four wavelengths. The intermediate frequency bandwidth was 50 MHz. Measurements were obtained on 1983 September 15 and 22, October 6, 19, and 30. The accuracy of the flux density measurements is 1 mJy at 20, 6, and 2 cm and 3 mJy at 1.3 cm.

[1] The Very Large Array (VLA) is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

III. RESULTS

Figure 1 displays the light curve for Cyg X-3 from 1982 October through 1985 March at 11.1 cm. The intense flaring events on 1982 September–October and 1983 September–October are present along with weaker events in 1983 February, 1984 September, and 1985 February–March. No data were collected during the period 1983 June 25–July 15 because of equipment malfunction. The major flaring event of 1982 September–October appears to be much simpler than that of 1983 September–October.

Periodicity in the occurrence in large outbursts (> 1 Jy) has been discussed by Woodsworth (1983). He found no evidence of periodicity between 10 and 50 days from examining the 19 flares reported over the time period 1972–1982. Figure 2*a* displays outbursts versus month of the year for 1972–1985. These are listed in Table 1. The flaring events prior to 1982 are those listed in Woodsworth (1983). These are all flaring events greater than 1 Jy. Single point observations with no indication of time of maximum were excluded. Figure 2*b* displays the number of outbursts versus month of the year. Events where several flares occurred in an outburst of activity, i.e., 1983 September–October are considered to be a single outburst in Figure 2*b*. Six of the 15 major outbursts occurred in September–October, and a total of nine occurred during

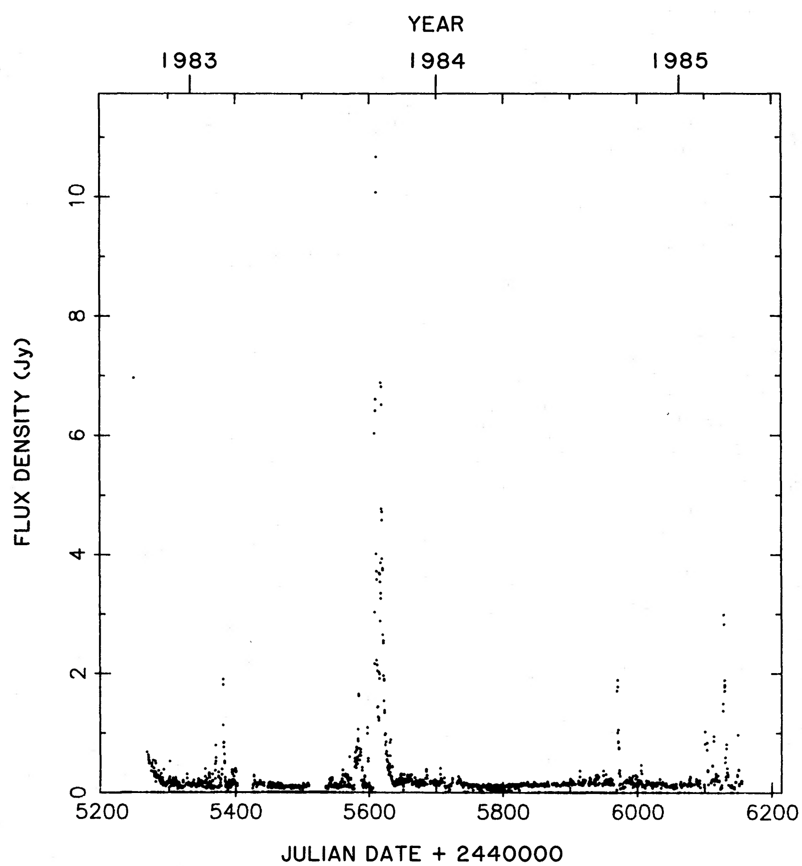

FIG. 1.—The 11.1 cm flux density of Cyg X-3 during the period 1982 October–1985 March. Note that in this time interval Cyg X-3 displayed flaring events of varying duration in 1982 September–October, 1983 February, 1983 September–October, 1984 September, and 1985 February–March. The time is given in Julian days and calendar years where 1983 = 1983 January 0 (JD 2,445,334.5).

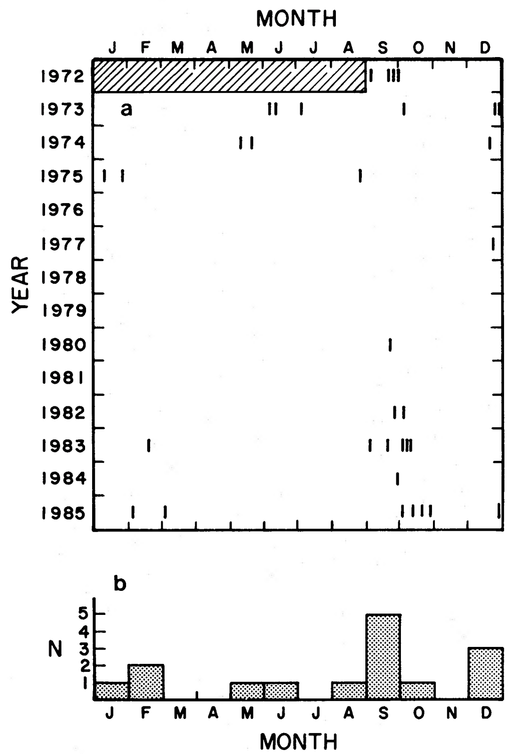

FIG. 2.—(*a*) The history of radio outbursts from Cyg X-3. The period from 1972 September–1982 October is taken from the literature as summarized by Woodsworth (1983). Note that the events of 1985 October and December appear on this figure but do not appear in the histogram. (*b*) The number of outbursts vs. month of the year. It is evident that the majority of outbursts happen in the months of September–October.

September–December. During the Green Bank monitoring period, when the data was continuous, there were always events in September–October and also in March–February 1983 and 1985. From inspection of Figure 2*b*, it would appear that a crude search for periodicity may be successful, and so an analysis very similar to that of Woodsworth (1983) was performed. The data from Table 1 were searched for periodicities in the range of 100–1000 days. Peaks in the periodogram occurred at 118.3 and 122.4 days and higher harmonics. This accounts for the outbursts in September–October, as well as those in the February–March time frame. The ~ 120 day period is estimated to be of 2σ reliability.

The results of the 1983 September–October campaign are shown in Figure 3. During the period before September 30, the flux density varied erratically between 2.2 and less than 0.1 Jy. The time scale of the variations is less than an hour. The 6 cm measurements of September 8, 11, 15, 16, and 20 show the flux density either increasing or decreasing smoothly but varying by as much as a factor of 3. The spectral indices are sometimes positive, sometimes negative. The large flare which began September 30 can be characterized as several individual flares which occurred between September 30 and October 3. After October 3, the emission appears to be dominated by another large flare, followed by another dominant flare on October 11. During October 3, the spectral index appears to be 0.1 ($S \approx \nu^{+\alpha}$). From October 3 to October 11 it is 0.0, while between October 11 and October 17, it goes from 0.2 to 0.4 while the flux density decays. Another small outburst occurs on October 25.

From these measurements it is seen that Cyg X-3 is extremely variable. In September the flux density varied from a few to less than 0.1 Jy. The flux density can easily vary by factors of 3 over a time scale of hours to days. This is typical of the extensive monitoring provided by earlier measurements (Gregory *et al.* 1975; Mason *et al.* 1976). The time variations may be characterized as containing spectral power from hours to days.

The 11 and 6 cm data were searched for periodicity in the range 0.1–10 days. No correlation was found for amplitudes greater than 50 mJy. Molnar *et al.* (1984; 1985) claim that low-level flares in the radio emission appear to have a periodicity of 4.95 hr with an amplitude that decreases with increasing radio wavelength. This was from an analysis of measurements made on 1983 September 17–18 and December 3–4. As can be seen from Figure 3, the September data were obtained during a period preceding a large outburst. Figure 4 is an expanded version of Figure 3 for September 8. On this day, Cyg X-3 was observed continuously for 15 hr. A large flare is seen at 15 hr UT, but no other flares of amplitude greater than 50 mJy follow this event 5 hr later. Inspection of the 6 cm data indicates that there are no definite flaring events every 4.8 or 4.95 hr with amplitudes greater than 50 mJy. Indeed, inspection of Molnar *et al.*'s data would appear to indicate the amplitude of any periodic phenomenon is less than 30 mJy.

The 6 cm data during 1983 September shows that this emission can further be characterized as being due to a succession of flares occurring on the dates given in Table 2. There is

TABLE 1

INDIVIDUAL LARGE FLARES

Date	Julian Date	Wavelength (cm)	Flux Density (Jy)	References
1972 Sep 2.5	2,441,563.0	2.8	22.	1
1972 Sep 20.6	2,441,581.1	6.0	12.	2
1972 Sep 23.5	2,441,584.0	11.	15.	2
1972 Sep 27.3	2,441,587.8	20.	12.	3
1973 Jun 8.0	2,441,841.5	6.	3.	4
1973 Jun 14.0	2,441,847.5	6.	7.	4
1973 Jul 1.3	2,441,864.8	2.8	7.	5
1973 Oct 8.2	2,441,963.7	2.8	4.	6
1973 Dec 24.1	2,442,040.6	7.1	8.	7
1973 Dec 31.	2,442,047.5	7.1	6.	7
1974 May 13.4	2,442,180.9	6.	7.	4
1974 May 20.0	2,442,187.5	3.7	12.	8
1974 Dec 19.1	2,442,400.6	7.1	5.	9
1975 Jan 10.	2,442,422.5	6.	10.	4
1975 Jan 29.5	2,442,442.0	3.8	7.	10
1975 Aug 25.	2,442,649.5	6.	15.	4
1977 Dec 18.7	2,443,496.2	1.3	4.	11
1980 Sep 26.9	2,444,509.4	1.3	10.	12
1982 Sep 28.9	2,445,241.46	11.1	20.	13
1983 Feb 16.8	2,445,382.28	11.1	1.9	14
1983 Sep 7.1	2,445,584.62	11.1	1.7	14
1983 Sep 20.1	2,445,597.64	11.1	1.1	14
1983 Oct 3.1	2,445,610.59	11.1	10.7	14
1983 Oct 8.9	2,445,616.45	11.1	3.7	14
1983 Oct 10.9	2,445,618.43	11.1	6.9	14
1984 Sep 29.9	2,445,972.45	11.1	1.1	14
1985 Feb 4.7	2,446,101.22	11.1	1.7	14
1985 Mar 3.7	2,446,128.19	11.1	2.3	14

REFERENCES.—(1) Gregory *et al.* 1972; (2) Branson *et al.* 1972; (3) Braes *et al.* 1973; (4) McEllin 1975; (5) Marsh *et al.* 1974; (6) Woodsworth 1983; (7) Daishido *et al.* 1974; (8) Seaquist *et al.* 1974; (9) Osawa 1974; (10) Ledden *et al.* 1976; (11) Domnin *et al.* 1980; (12) Steshenko *et al.* 1980; (13) Geldzahler *et al.* 1983; (14) this paper.

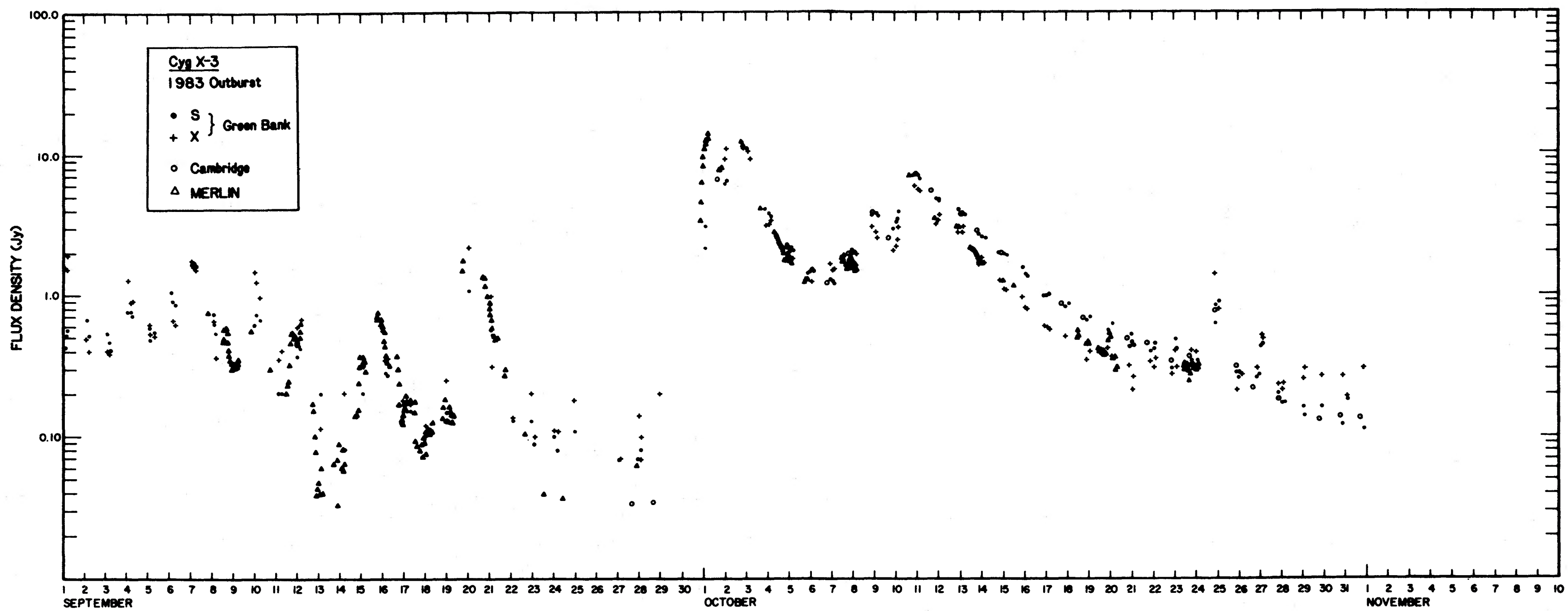

FIG. 3.—The flux density for the months of 1983 September–October. The filled circles (●) and plus signs (+) denote the Green Bank 11.1 and 3.75 cm measurements, the open circles (○) denote the Cambridge 11.1 cm data, and the open triangles (△) denote the MERLIN 6 cm data.

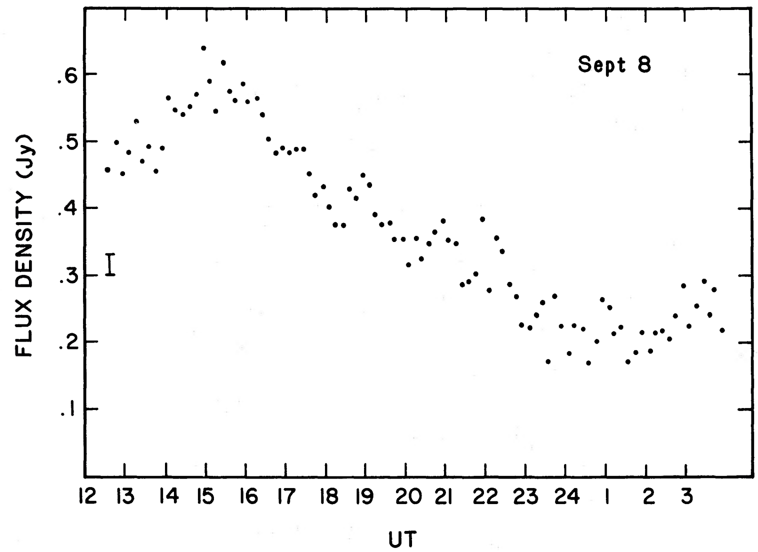

FIG. 4.—The 6 cm flux density for 1983 September 8–9. There is a large flare evident at 15 hr UT September 8, but no repetition of this flare at 20 hr UT September 8 and 01 hr September 9 at levels of 100 mJy.

extensive data on September 13, 18, and 19, but it is difficult to establish the time of a flare because the flux density is monotonically increasing, decreasing, or varying erratically. The large errors on some of the epochs reflect the fact that it is often difficult to determine definite maxima. An analysis similar to that performed for the large flaring outbursts did not lead to a definitive period. Table 2 lists the times of maxima for flares in the 6 cm data for 1983 September–October. Because of the large errors in the flare epochs, which have errors of 0.02 to 0.2 days, almost any period near 4.8 hr will fit the data.

IV. DISCUSSION

The flux density of Cyg X-3 can best be characterized as being made up of individual flares that vary in intensity from less than 0.1 to 20 Jy, a factor of 1–200. These flares have time scales of hours to days. We have shown that the intensity of these flares, if they occur with periods of 4.8–4.9 hr, have recurrent amplitudes of less than 50 mJy at 6 cm. Large flaring outbursts appear to cluster in the months of September–October. However, the historical record is very incomplete. The continuous monitoring by the Green Bank interferometer is from 1982 September to 1985 March. From 1972 September to 1982 September, sporadic measurements were made. It does appear to be more than coincidental that six out of 15 major events happened during September–October.

Models for the radio emission from Cyg X-3 have been developed by Davidsen and Ostriker (1974) and van den Heuvel and De Loore (1973) which interpret the periodic X-ray emission as due to a binary star system in which the periodic X-ray and IR emission are due to mass transfer from one member of the binary system, which fills its Roche lobe, onto a compact companion. This binary star system is surrounded by a dense cocoon of circumstellar material. The radio emission originates from relativistic electrons accelerated in a dense stellar wind by a blast wave propagating out from the collapsed star due to radio pressure from the X-ray event caused by the initial infall material (Seaquist 1976).

TABLE 2

TIMES OF FLARES

UT (days)	
1983 September	1983 October
8.4 ± 0.02	1.3 ± 0.1
11.78 ± 0.07	2.8 ± 0.2
15.028 ± 0.05	10.8 ± 0.1
15.75 ± 0.05	19.96 ± 0.05
19.8 ± 0.2	25.0 ± 0.2
20.712 ± 0.05	

Cygnus X-3 can be better understood when compared to similar X-ray sources. Two X-ray sources 2A/4U 1822−371 (V691 Cr A) and 4U 2129+470 (V1727 Cyg) have periods of X-ray and optical modulation of 5.57 and 5.2 hr, respectively. They are also much less reddened [$E(B-V) = 0.5$ and 0.1 mag, respectively], while Cyg X-3 has a value of 6.5 mag). These two systems display accretion disk coronae of 0.6 and 0.3 $R_\odot$ (White and Holt 1982). It may be inferred that Cyg X-3 also consists of a binary star system with an accretion disk corona from similarities among these three objects. The shape, stability, and modulation of their X-ray light curves are similar. The low state X-ray emission of Cyg X-3 and 4U 1822−371, as well as the X-ray luminosities of Cyg X-3 (10^{37}–10^{38} ergs s^{-1}) 4U 1822−371 ($>10^{36}$ ergs s^{-1}) and 4U 2129+470 (10^{35} ergs s^{-1}) are also similar. Thus a large cocoonlike envelope is not necessary to explain the observed properties of Cyg X-3 such as the X-ray and UV eclipses and short-term intrinsic X-ray variations. These can best be accounted for by asymmetries or bulges in an accretion disk. This bulge is where a stream of matter from the companion star impinges on the outer edge of the accretion disk (White and Holt 1982; White *et al.* 1981). The major differences in the three objects are caused by the inclination of the plane of the orbit to the line of sight (Cyg X-3 = $<70°$; 4U 1822−371 = $\sim 75°$; 4U 2129+470 = $\sim 82°$). Further credence is given to the presence of an accretion disk corona in Cyg X-3 as the mass of the secondary star is estimated at 0.9 $M_\odot$ for an inclination of 70°. A star of this mass would have too low a luminosity to create a strong stellar wind and high mass loss rate needed for the cocoon model (White and Holt 1982).

Any possible mechanism for periodic flares in Cyg X-3 must modulate the mass infall rate onto the collapsed star. For the binary star Cir X-1, periodic X-ray flaring events are probably caused by an elliptic orbit which allows increased mass transfer during close approach of the stars (Murdin *et al.* 1980; Haynes *et al.* 1980). This mass transfer is due to accretion of matter onto the collapsed star from the stellar wind or overflow from the Roche lobe near or at the time of periastron passage. This mechanism would make possible correlation of the radio emission of Cyg X-3 with its 4.8 hr orbital period if the orbit were elliptical. The 120 day flaring events cannot be accounted for by apsidal motion since the period of the 4.8 hr orbital period has not shown any yearly variation in the shape of the X-ray light curve. Further measurement of time of minima indicate that the period of 4.8 hr is decreasing by 5×10^{-9} yr^{-1} (Lamb, Dower, and Fickle 1979; Manzo, Molteni, and Robba 1978; Elsner *et al.* 1980; van der Klis and Bonnet-Bidaud 1981). Elsner *et al.* (1980) estimate period of apsidal motion to be greater than 22 yr since the asymmetry in the X-ray light curve has persisted unchanged for more than 5 yr and the apparent decrease in the orbital period at this time seems to be constant. A continuous 30.6 hr observation of the X-ray emission (Willingale, King, and Pounds 1985) shows considerable short-term variations. However, these variations would probably not mask short-period apsidal motion. Thus it appears unlikely that the 120 day flaring events are due to apsidal motion.

A second possibility could be precession in the beam of material emitted by Cyg X-3 similar to the 164 day period of precession of SS 433. This would cause the line of sight between us and the beam ejection axis to vary. However, the velocity of the ejected plasma is likely to be less than 0.35 c (if the distance to Cyg X-3 is of order 12 kpc), making any amplification of the radiation, due to beaming along or close to the line of sight, less than 10%.

Motions of the accretion disk could alter the accretion rate. A possible cause of this is the presence of a third body. This third body must have about a 120 day orbital period in a slightly elliptical orbit around the binary system. This third body does not have to be very massive to trigger a major accretion event onto the collapsed star. The observed high and low rates in the X-ray as, well as the observed X-ray flares, suggest a variable accretion rate.

V. CONCLUSIONS

The flux density of Cyg X-3 has been monitored by the Green Bank interferometer from 1982 October through 1985 March. Large flaring events occurred in 1982 September–October, 1983 February, 1983 September–October, 1984 September, and 1985 February–March. The historical record shows that Cyg X-3 has displayed 15 such flaring events. Six of these events have taken place during the months of September–October. A periodogram analysis shows the possibility of 120 day variation at a level of 2 σ reliability. It would appear that this is more than a chance coincidence and may be due to the modulation of the accretion rate by the presence of a third body in the Cyg X-3 star system. This would predict a strong correlation between X-ray and radio emission during intense radio flares.

An intense active event occurred in 1983 September–October. This event was also monitored extensively at 6 cm. The flux density varied on time scales of hours to days with random variation at the 100 mJy level. Most of this emission could be ascribed to a multitude of flaring events merged together. From a detailed analysis of this data, there are no variations of period 4.8–4.9 hr with amplitudes greater than 50 mJy at 6 cm. This does not rule out periodic lower level radio emission.

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