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SIMULTANEOUS X-RAY AND INFRARED OBSERVATIONS OF CYGNUS X-3

K. O. MASON[1]
Mullard Space Science Laboratory
F. A. CÓRDOVA[1]
Los Alamos National Laboratory
AND
N. E. WHITE
EXOSAT Observatory, ESOC
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ABSTRACT

Cygnus X-3 has been observed simultaneously in the X-ray and infrared spectral bands. A series of short (few minute duration) flares were detected in the infrared. The most intense of these involve a doubling of the 2.2 μm flux. No counterparts of the flares were unequivocably detected in the X-ray band; the ratio of the flare energy emitted in the 1.5–10.0 keV and 2.0–2.4 μm bands is <40. We interpret the infrared flare events as emission from clumps of hot material being ejected from the system in jets and predict that they are the precursors of radio flares which originate in outlying jet regions. In addition to the flares, the infrared emission is modulated with the 4.8 hr X-ray period. The shape of the 4.8 hr modulation is remarkably similar in the infrared and X-ray bands, although the fraction of the emission that is modulated is much smaller in the infrared.

Subject headings: infrared: sources — stars: individual — X-rays: binaries

I. INTRODUCTION

The X-ray source Cygnus X-3 remains an enigma despite more than a decade of study. The X-ray flux is modulated with a stable 4.79 hr period (van der Klis and Bonnet-Bidaud 1981; Willingale, King, and Pounds 1985; and references therein) that is usually thought to reflect the orbital motion of the system. Cyg X-3 is a spectacular flaring radio source (e.g., Gregory *et al.* 1972) from which a number of strong outbursts have been detected. Recent work suggests that the low-level radio emission normally present between outbursts is comprised of small flares which recur with a period (4.95 hr) that is significantly longer than the X-ray modulation period (Molnar, Reid, and Grindlay 1984, 1985). Cyg X-3 has probably also been detected in the ultra–high-energy gamma-ray part of the spectrum (energies of 10^{12}–10^{16} eV) and may be a dominant source of 10^{17} eV cosmic rays in the Galaxy (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983; Hillas 1984; Porter 1984). Although not detected in the optical band because of high interstellar extinction, Cyg X-3 is a bright infrared source. The infrared flux is sometimes modulated in phase with the 4.8 hr X-ray period, and infrared flares have also been detected (Mason *et al.* 1976; Becklin *et al.* 1973, 1974). The X-ray and infrared flux levels both undergo variations on time scales of days to weeks.

In this paper we report simultaneous X-ray and infrared photometry of Cyg X-3 carried out with ESA's *EXOSAT* X-ray observatory, and the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. In the decade since the only other observations of this kind were undertaken (using the *Copernicus* satellite, and the 200 inch [5 m] Mount Palomar and 100 inch [2.5 m] Mount Wilson telescopes), the sensitivity of the instrumentation available in both bands has increased dramatically. The new data enable the X-ray and infrared light curves to be compared in unprecedented detail and allow us to confront the predictions of various source models.

II. OBSERVATIONS

a) Infrared

Approximately 5 hr of data on Cyg X-3 were obtained under photometric conditions on the night of 1984 September 2 UT using the 3.0 m NASA Infrared Telescope Facility on Mauna Kea and the InSb detector cooled with liquid helium. A further 2 hr of data were obtained the following night under non-photometric conditions. A 6″ aperture was chopped between the target star and a nearby region of blank sky at a rate of 7 Hz. The size of the chopping offset was 10″ at a position angle of 0°. The target was placed alternately in the left- and right-hand beams and the difference between the source and background signal integrated for 5 s in each beam. Pairs of points were combined to yield the light curve of the star. The mean interval between successive points on the light curve is about 12 s when the dead-time associated with the beam switching is included.

Cyg X-3 was observed with a standard *K* band filter (center 2.2 μm). Observations of the target were interspersed, at intervals of between 30 and 60 minutes, with observations of a nearby SAO star to check the long-term photometric quality of the sky and to provide an atmospheric extinction correction. A *K* band standard star, 61 Cyg B, was observed to calibrate the instrument and to relate the data to an external photometric system.

b) X-Ray

EXOSAT observed Cyg X-3 for about 10 hr on both 1984 September 2 and 3 UT coincident with the time that the source was above the horizon at Mauna Kea. Of primary interest here

[1] Visiting Astronomer at the Infrared Telescope Facility which is operated by the University of Hawaii under contract to the National Aeronautics and Space Administration.

are data from the Medium Energy (ME) Proportional Counter array which was operated in offset mode (half the array pointed at the source; the other half pointed at blank sky to monitor the background count rate). X-ray pulse height spectra were obtained every 10 s from each of the detectors making up the ME array, over a useful energy range of 1.5–20 keV.

III. RESULTS

The simultaneous X-ray and *K* band infrared data on Cyg X-3 obtained on September 2 U.T. are plotted in Figure 1 and cover just over one 4.8 hr cycle of the source. The infrared data have been corrected for atmospheric extinction. The X-ray data in the figure are from the ME argon modules and have been accumulated in two energy bands, 1.5–6.0 keV and 6.0–10.0 keV. Also plotted is the ratio of the flux density in these two bands. The conversion factors between count rate and flux density for a spectrum similar to that of Cyg X-3 are 1.0 μJy per (counts s^{-1} [half array]$^{-1}$) and 2.1 μJy per (counts s^{-1} [half array]$^{-1}$) averaged over the 1.5–6.0 and 6.0–10.0 keV bands, respectively. The X-ray data show the 4.8 hr modulation typical of the source, with a hardening of the spectrum near minimum flux (cf. Willingale, King, and Pounds 1985). This periodic spectral hardening is superposed on a monotonic increase in the (6.0–10.0 keV) to (1.5–6.0 keV) flux ratio through the observation.

a) Flares

The most striking feature of the infrared light curve is a series of short intense flares which involve up to a twofold increase in flux. Because the observations were made in chopping mode, we can be confident that these flares arise in the source and are not artifacts of the detector. The flares occur throughout the 4.8 hr cycle covered. They typically last for between 2 and 10 minutes and sometimes occur multiply. Rise times are as short as 1 minute. The two strongest flare events

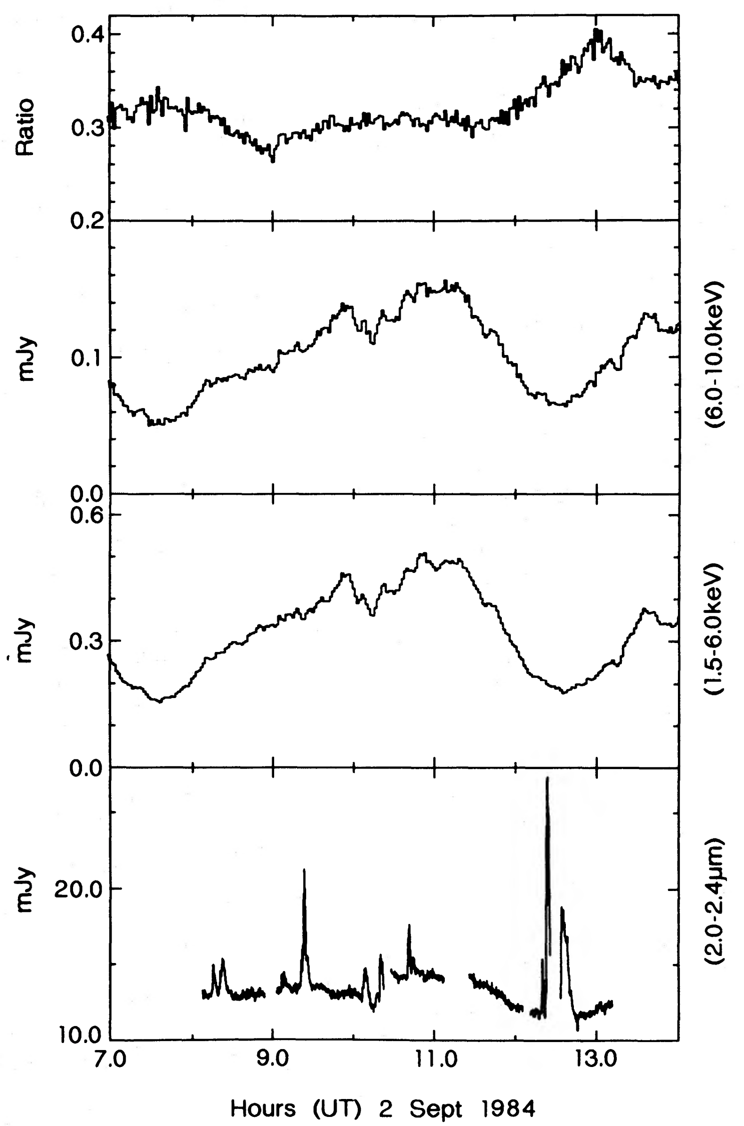

FIG. 1.—Infrared and X-ray light curve of Cygnus X-3 measured on 1984 September 2. Note that the zero point of the infrared light curve (*lowest panel*) has been offset to show the 4.8 hr modulation to better effect. The X-ray data are shown in two energy bands, both from the argon modules of the ME detector. The top panel shows the ratio of the 6.0–10.0 keV flux to the 1.5–6.0 keV flux.

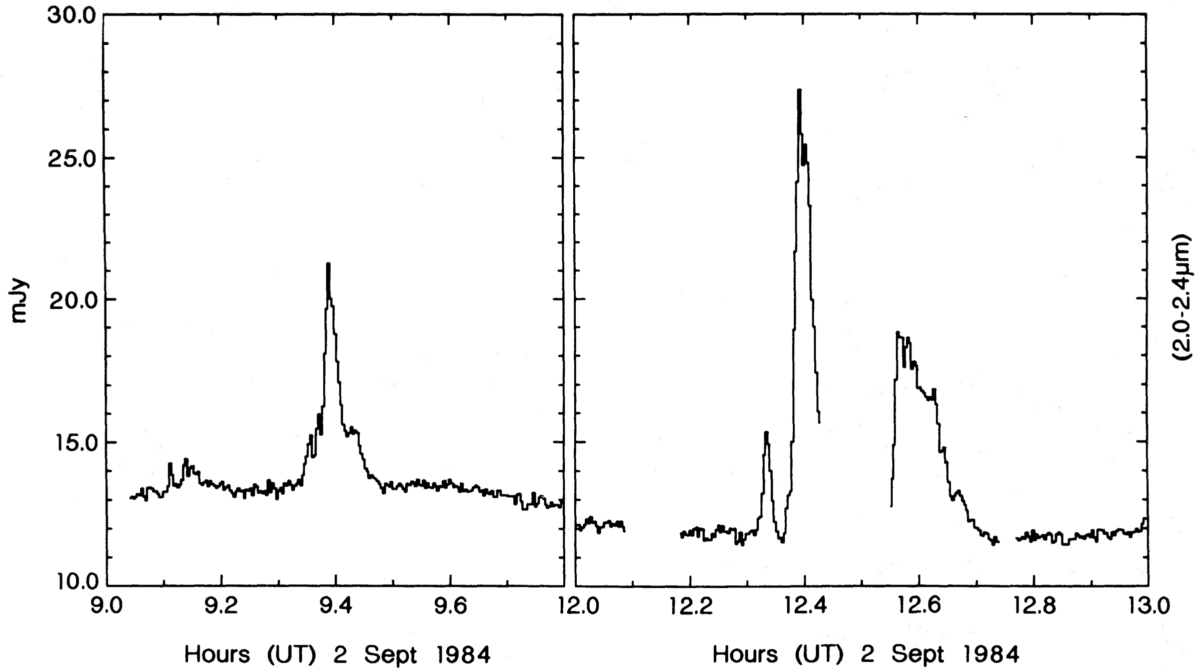

FIG. 2.—Principal infrared flares from Fig. 1 shown on an expanded time scale.

recorded are shown on an expanded scale in Figure 2. The total amount of energy contained in these two flare complexes is 2.6×10^{-10} ergs cm^{-2} and $>9.4 \times 10^{-10}$ ergs cm^{-2}, respectively, for the events beginning at 9:20 UT and 12:20 UT. The energy in the latter is a lower limit because of the break in coverage that occured during the flare.

It is of obvious interest to establish whether there are X-ray flares corresponding to the infrared events. Inspection of Figure 1 reveals no clear-cut case of such an X-ray flare counterpart. However, there is a possible flarelike event in the X-ray flux just before the strongest of the IR flares. The X-ray event began at 12:16 UT and lasted for about 8 minutes, whereas the infrared activity begins with a small flare starting at about 12:19 UT. We do not see X-ray events associated with other, weaker, infrared flares in our data, but we would not expect to if the strength of the X-ray events scales linearly with the infrared flare strength. It is not clear whether the X-ray event at 12:16 UT is related to the infrared flare. X-ray flux variations with this amplitude and time scale are not unusual in the light curve of Cyg X-3. The spectrum of the flare at 12:16 UT may be slightly harder than normal; it is most noticeable in the 6.0–10.0 keV band and is also discernible in the poorer signal-to-noise ratio 10–20 keV data (not shown) taken from the xenon modules of the ME. Otherwise, there is nothing remarkable about it apart from its coincidence with the IR flare, and we would need to identify several more such coincidences before being convinced that the X-ray and infrared flares were related. Interestingly, an X-ray fluctuation of similar character occured during the previous 4.8 hr cycle, before the beginning of our infrared coverage. The separation of the two X-ray "flares" is just over one 4.8 hr cycle.

Because of the relationship of the X-ray and infrared flares is uncertain, we use the magnitude of the X-ray event to provide an upper limit to the X-ray flux associated with the infrared flare at 12:20 UT. The total energy emitted in the 1.5–10.0 keV band in the X-ray event is estimated to be 2×10^{39} ergs at a distance of 11 kpc, summed over its 400 s duration and corrected by a factor of 2.2 for interstellar absorption. In contrast, about 5×10^{37} ergs was emitted in the K band (2.0 and 2.4 μm) between 12:19 and 12:40 UT allowing for 1.5 mag of interstellar absorption (Becklin *et al.* 1972). Thus the ratio of the 1.5–10 keV to K band emission during the flare was <40. In comparison, the ratio of the instantaneous nonflare energy flux integrated over the 1.5–10.0 keV and K bands is ~ 1000.

b) The 4.8 Hour Modulation

The 2.2 μm flares in Cyg X-3 are superposed on a shallow 4.8 hr modulation of the infrared flux which is in phase with the 4.8 hr X-ray modulation. The pulsed fraction of the infrared modulation is 10%, compared to 50% in the 1.5–6.0 keV X-ray band. In Figure 3 we have superposed the infrared and 1.5–6.0 keV X-ray light curves of Cyg X-3, having normalized the scale of the y-axis to the amplitude of the 4.8 hr modulation in each case. This is equivalent to subtracting a DC signal of 10 mJy from the 2.2 μm data. We note from Figure 3 that, apart from the flares, there is very good agreement between the shapes of the light curves in the two bands. An exception occurs at about 10:00 UT when there is a 4% drop in the infrared flux lasting for about 30 minutes at the same time as the X-ray flux increases by $\sim 10\%$. This is followed by a narrow (10 minute) dip in both bands. Such variability, with a time scale of about 30 minutes and an amplitude of about 10%, is common in the X-ray flux of Cyg X-3. Indeed, the 4.8 hr cycle over which we obtained simultaneous X-ray and infrared coverage was unusually devoid of such X-ray variability.

A further 2 hr of infrared data were obtained between 11:00 and 13:00 U.T. on September 3 through thin cirrus. The 4.8 hr modulation was clearly present. Although the nonphotometric conditions do not allow us to comment on the detailed shape of the light curve, there is no evidence for substantial flares of the kind recorded on September 2.

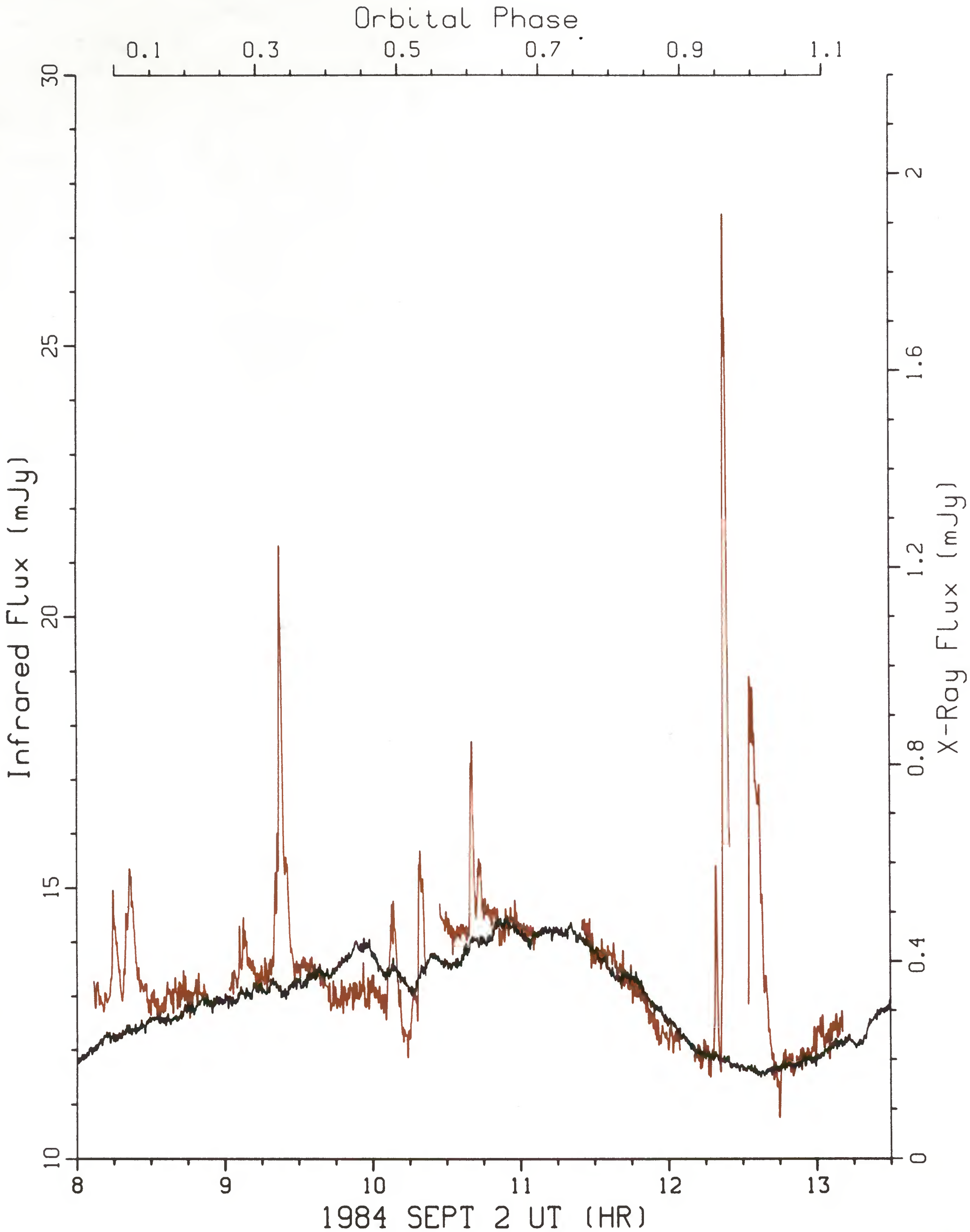

FIG. 3.—Superposition of simultaneous X-ray and infrared data. The X-ray data are from the 1.5–6.0 keV energy range. The data have been scaled so that the amplitude of modulation is the same in both bands.

IV. DISCUSSION

a) Infrared Flares

The K band photometry of Cyg X-3 presented here have the shortest time resolution (12 s) and the highest sensitivity yet published for this star. As a consequence, we detect faster, lower luminosity flares than have heretofore been observed. The flare with the largest peak flux occured during the minimum of the 4.8 hr cycle (Fig. 2) and had a rise time of 60 s, a duration (i.e., the full width at the base of a triangular shaped flare) of 400–600 s, and a total K band energy of $\sim 5 \times 10^{37}$ ergs at 11.6 kpc (allowing for 1.5 mag of interstellar extinction). Smaller flares with a similar duration but with total fluxes as much as a factor of 10 lower occur throughout the binary cycle.

i) Comparison with Previous Observations

Previous published infrared photometry of Cyg X-3 has been confined to scattered observations made during 1973 using the 200 inch Mount Palomar telescope (Becklin *et al.* 1973, 1974) and a more intensive campaign that lasted for 2 weeks in 1974 September and which used the 100 inch Mount Wilson telescope (Mason *et al.* 1976). Many of these observations were made simultaneously with observations of Cyg X-3 in the X-ray and radio bands.

An infrared flare has been recorded on two previous occasions (Becklin *et al.* 1974). On 1973 July 11 a flare of amplitude 8 mJy that lasted for about 6 minutes was observed just after the minimum of the 4.8 hr intensity cycle. The mean 2.0–2.4 μm flux level of the source at this time was about 15 mJy. Details of the flare structure were not resolved. The amplitude and time scale of this flare, though, are very similar to the large flare complex observed by us at 12:30 UT on September 2, also close to minimum in the 4.8 hr cycle. Note that the smaller flares that we observed in 1984 would not have been resolved in the 1973 and 1974 data because of the relatively poor signal-to-noise ratio.

The second infrared flare observed by Becklin *et al.* (1974) had a much different character than the first flare, and also different than the flares which we report in the present paper. This was observed on 1973 August 12 when the 2.0–2.4 μm flux increased from a mean of 18 mJy to 45 mJy. This flare lasted for 1.5 hr and there was evidence for structure on a time scale as short as the 5 minute separation between data points. X-ray and radio coverage were obtained during this observation. There was no evidence for any disturbance of the 2.5–7.5 keV X-ray light curve during the infrared flare, while the 3.8 cm radio flux, though low, was apparently decaying from a radio flare that probably occured about 2 hr before the infrared event. There was no radio coverage after the infrared flare.

ii) Origin of the Infrared Flares

What is the origin of the infrared flares and how do they relate to the flaring radio emission? Radio observations between 1.3 and 20 cm show that continuous low-level radio flaring is a characteristic of Cyg X-3's "low" state (Molnar, Reid, and Grindlay 1984, 1985). The rise time of the radio flares is ≥ 3000 s, and they last for several thousand seconds, much longer than the few minute duration of the IR flares. (Molnar privately communicates that more recently he has observed lower amplitude radio flares with a duration of only 30 minutes, but these are still considerably longer than the IR flares.)

The properties of the low-state radio flares observed by Molnar, Reid, and Grindlay (1984) are consistent with a model in which relativistic particles emitting synchrotron radiation are injected into a small volume which subsequently expands with a constant velocity (Shklovski 1965; van der Laan 1966; Kellermann and Pauliny-Toth 1968). Such a model predicts, in agreement with the observations, that the longer the wavelength, the later the time of maximum flux, and the lower the maximum flux density of the flare. A similar mechanism can account for the giant radio flares observed in Cyg X-3 (e.g., Gregory *et al.* 1972). The latter seem therefore to differ from the low-state flares only in degree.

Molnar, Reid, and Grindlay (1984) calculate that the minimum size of the "low-state" radio flare emitting region is about 6×10^{12} cm. The short rise time, ~ 60 s, of the infrared flares suggests that these come from a much smaller volume, whose dimensions, limited by light travel time, must be $< 10^{12}$ cm. The radio flare emission of Cyg X-3 has been resolved into a double-lobed structure that expands with a velocity of about one-third the speed of light, indicative of a jet (Gelzahler *et al.* 1983; Spencer *et al.* 1986; Molnar 1985). We suggest that the infrared flares are emission from hot clumps of matter in the inner parts of this jet which are being ejected from the binary system, and that these same clumps are responsible for the radio flares when they become optically thin to radio synchrotron emission further out in the jet. If this idea is correct, each IR flare should be the precursor of a radio event, a prediction that can easily be tested by simultaneous infrared and radio observations.

To illustrate that the above model for the origin of the infrared flares is reasonable, we consider a uniform cloud of gas emitting bremsstrahlung radiation at a temperature of, for example, 10^6 K. The K band flux at the peak of the strongest flare (~ 16 mJy) implies an emission measure $\int Ne^2 dV \approx 1.5 \times 10^{61}$ at 11.6 kpc, allowing for interstellar extinction. Thus if the radius of the cloud is 10^{11} cm, similar to the inferred binary separation of Cyg X-3, the mean density of the cloud is $\sim 10^{14}$ cm^{-3}, and the column density across it is $\sim 10^{25}$. Alternatively, if the cloud has the maximum radius of 10^{12} cm determined by the rise time of the flares, the density is reduced to $\sim 2 \times 10^{12}$ cm^{-3}. The observed decay time of the K band flares is as short as ~ 100 s, which could be accommodated by bremsstrahlung cooling provided that the density of the cloud is $> 5 \times 10^{11}$ cm^{-3}. Adiabatic expansion may also be important in determining the flare decay rate depending on whether and how the matter in the jet is confined. Reasonable estimates of the density of the infrared emitting cloud suggest that the cooling time of the gas will be much less than the typical time length of the flares. Thus the duration of the infrared flares is probably determined by the duration of the particle injection event into the jet.

Molnar, Reid, and Grindlay (1985) confirm their earlier suggestion (Molnar, Reid, and Grindlay 1984) that dominant radio flares from Cyg X-3 recur with a period (4.95 hr) that is significantly longer than the orbital period (4.79 hr). The IR data of 1984 September 2 demonstrate that many IR flares can occur during one 4.8 hr cycle. However $\frac{2}{3}$ of the IR flare energy that we detected was contained in the one flare complex at $\sim$12:20 UT. Because of the longer time scale of the flares at radio wavelengths, multiple flares occurring as often as in our infrared data would not be cleanly resolved in the radio band, although, as noted above, L. A. Molnar (private communication) does detect time structure in some radio flares. It remains to be seen whether the probability of large infrared flares also exhibits the 4.95 hr periodicity found in the radio data.

It should be noted that the data of Becklin *et al.* (1974) and Mason *et al.* (1976) suggest that IR flares as large as the largest we detected on 1984 September 2 do not occur on every cycle. Further, as mentioned previously, an IR flare that was longer and much more energetic than the brightest reported here was detected by Becklin *et al.* (1974). Thus, like the radio flares, the IR flares apparently have a large spectrum of time scales and amplitudes.

Although no radio observations were made at exactly the same time as our X-ray and infrared observations, the results of long-term monitoring observations suggests that the radio source was in an intermediate activity state at the time of our observations (K. Johnston, private communication; Johnston *et al.* 1986).

b) The 4.8 Hour Light Curve

Previous infrared observations (Becklin *et al.* 1974; Mason *et al.* 1976) did not always detect a significant 4.8 hr modulation of the *K* band flux. In some cases it is clear that the light curve is distorted by unrelated variability, but it is also probable that the pulse fraction of the 4.8 hr infrared modulation varies with time. Pulse fractions of about 15% were measured by Mason *et al.*, while Becklin *et al.* show one cycle where the pulse fraction is probably $\sim 25\%$. The pulse fraction of 10% measured in the present data would have been difficult to detect in the lower signal to noise observations of Mason *et al.* (1976). It is also clear that the mean *K* band flux per 4.8 hr cycle (excluding obvious flares) also varies with time, from ~ 14 mJy (Mason *et al.* 1976; present work) to about 25 mJy (Becklin *et al.* 1974). The visibility of the 4.8 hr modulation is not, however, apparently related simply to the mean IR flux level of the source.

A striking feature of the 4.8 hr infrared light curve which we measured on 1984 September 2 is the similarity between its shape and that of the X-ray light curve obtained simultaneously. This confirms, at a better signal-to-noise level, the result found by Mason *et al.* (1976) who compared the mean of three 4.8 hr cycles of infrared data where the modulation was prominent with simultaneous X-ray measurements.

Several models have been put forward to explain the 4.8 hr light curve of Cyg X-3 (e.g., Treves 1973; Bruhweiler 1973; Basko, Sunyaev, and Titarchuk 1974; Pringle 1974; Davidsen and Ostriker 1974; Milgrom 1976; White and Holt 1982). These have enjoyed varying degrees of success in explaining the observations. Two ideas that have been discussed in the recent literature are the stellar wind scattering model (Willingale, King, and Pounds 1985) and an accretion disk corona model (White and Holt 1982). Given the right conditions, as explained below, both of these models can account for the observed agreement in shape between the X-ray and infrared light curves.

In the stellar wind scattering model, suggested originally by Pringle (1974) and Davidsen and Ostriker (1974), the X-ray source is surrounded by an optically thick scattering cloud which is centered on the mass-donating companion star. The X-ray source is offset from the center of the cloud and the resulting asymmetry causes the modulation with the binary orbital period. In the variant of this model considered by Willingale, King, and Pounds (1985), the asymmetry of the 4.8 hr X-ray light curve is caused by an accretion wake that trails the X-ray source. (A similar explanation of the asymmetry was also put forward by Mason 1976). The irregular variability often seen in the light curve is explained as due to inhomogeneities in the wind. The structure of the accretion wake is unlikely to be maintained over large radial distances. Thus, the similar shape of the X-ray and infrared light curves, interpreted according to this model, suggests that the effective "photosphere" of the cloud is at essentially the same radius in both the X-ray and infrared bands. To satisfy this condition, electron scattering must dominate the opacity of the cloud in the infrared as well as at X-ray wavelengths. If the cloud density at a distance of 10^{11} cm is $n_e \approx 10^{13}$ cm^{-3} (chosen to give unit electron scattering optical depth through the cloud to the X-ray source at conjunction; Willingale, King, and Pounds 1985), we calculate that the cloud temperature must be greater than 10^5 K for free-free absorption to be negligible in the infrared compared to electron scattering. Unmodulated, optically thin free-free emission from the cloud at large radial distances will dilute the pulse-fraction of the 4.8 hr modulation in the infrared, while photoelectric absorption within the cloud may accentuate the modulation at low X-ray energies.

In the model of White and Holt (1982), originally developed to explain the light curve of the partially eclipsing X-ray source X1822−371 (Bradt and McClintock 1983), the X-ray emitting star is enveloped in a cloud of hot matter that is evaporated from an accretion disk (rather than from the companion star as in the stellar wind model). X-rays are scattered into the line of sight by this material which may be a quasi-static atmosphere, or a wind being blown off the accretion disk. The 4.8 hr modulation is caused by azimuthal structure in the height of the outer accretion disk which modulates the visibility of the cloud with the orbital period. If the cloud also emits the free-free photons which we observe in the infrared, both the X-ray and infrared emission will be modulated in the same way by the structure of the disk, and the light curve will be similar in the two bands. As in the stellar wind model, any free-free emission from optically thin material beyond the edge of the disk will contribute an unmodulated infrared component, while photoelectric absorption in disk material will again accentuate the modulation depth at low X-ray energies. The hot disk itself is probably a minor source of infrared radiation in Cyg X-3, unlike X1822−371 (e.g., Mason and Córdova 1982); if we calculate the expected blackbody flux from the heated edge of the disk assuming it to be at a radius of 4×10^{10} cm from a 10^{38} ergs s^{-1} X-ray source, or scale the flux observed from X1822−371 to the distance of Cyg X-3, we find that the apparent *K* magnitude of the hot disk is expected to be about 18, compared to the observed *K* magnitude of Cyg X-3 of ~ 11.5.

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France A. Córdova: MS D436, Los Alamos National Laboratory, Los Alamos, NM 87545

Keith O. Mason: Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey, U.K.

Nick E. White: *EXOSAT* Observatory, ESOC, Robert Bosch Strasse 5, 6100 Darmstadt, W. Germany