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VLBI OBSERVATIONS OF A RADIO FLARE OF CIRCINUS X-1

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ABSTRACT

A strong (~ 1.2 Jy) radio flare of the binary star system Circinus X-1 was observed with VLBI at three southern hemisphere observatories. The 2.3 GHz observations were made from 1980 April 22 to 28 and commenced 1 day prior to the flare outburst. Throughout the observation period, the flaring component of the radio source had an angular size, θ, in the range $0''.0015 \lesssim \theta \lesssim 0''.015$. This is equivalent to a linear size of 15–150 AU at the 10 kpc distance of Circinus X-1. However, scattering in the interstellar medium may have enlarged the apparent angular source size. The mean expansion velocity of the flaring component was found to be $\lesssim 0.1c$.

The quiescent component of the radio source observed prior to the flare was found to have an angular size of $\gtrsim 0''.2$. This is equivalent to a linear size of $\gtrsim 2000$ AU at 10 kpc. Hence, the quiescent radio emission comes from a region much larger than that proposed in recent models for Circinus X-1. The quiescent component appears to be variable on a time scale of years and is probably fueled by the Circinus X-1 binary system.

Subject headings: interferometry — stars: binaries — stars: flare — stars: individual — stars: radio radiation

I. INTRODUCTION

X-ray, optical, infrared, and radio observations indicate that Circinus X-1 is probably a binary star system at a distance of 10 kpc with a period of 16.59 days (Kaluzienski *et al.* 1976; Whelan *et al.* 1977; Goss and Mebold 1977; Glass 1978; Thomas *et al.* 1978; Haynes *et al.* 1978; Nicolson, Feast, and Glass 1980). A most intriguing property of this source is the periodic (16.59 day) precipitous dropoff in observed X-ray flux which is nearly coincident with the initiation of flaring at longer wavelengths. A theoretical model for the binary system has been proposed (Haynes *et al.* 1979; Murdin *et al.* 1980; Haynes, Lerche, and Murdin 1980) in which mass transfer is occurring from a primary star ($M_p \sim 20\ M_\odot$) to a compact companion star ($M_c \sim M_\odot$) in a highly eccentric orbit ($e \sim 0.8$) with apastron and periastron distances of ~ 2 and 0.1 AU respectively. According to this model, the observed radio flaring with the binary period is due to matter being transferred to the compact star near the time of periastron passage. It is argued that at this time the accretion rate exceeds the critical Eddington rate, and one or more expanding shock fronts are produced by radiation pressure pushing outward on the infalling material. At time t (in seconds) after formation, the shock wave radius is $\sim 3 \times 10^9\ t^{4/7}$ cm. Synchrotron self-absorption inhibits radio radiation until the shock wave expands enough to become transparent, causing the radio flare peak to appear first at higher frequencies. This is consistent with existing observations (Haynes *et al.* 1978). The model also suggests that the weak steady radio emission that has been observed during the quiescent phase of the 16.59 day cycle (Whelan *et al.* 1977; Haynes *et al.* 1978; Thomas *et al.* 1978) is due to relativistic electrons produced in the shock wave leaking into the accretion disk and giving rise to optically thin synchrotron emission.

The highest angular resolution (~ 40″) observations of the radio emission from Circinus X-1 prior to this *Letter* were obtained with the Fleurs synthesis telescope at 1.4 GHz (Haynes *et al.* 1978). The resulting map shows a weak, extended region centered 1′ south of the flaring point source. Using the Molonglo telescope, Little (1978) suggested that the 408 MHz source associated with Circinus X-1 possibly has a steady, extended radio component located up to 30″ southeast of the optical source together with a smaller variable component more closely associated with the optical position. In this *Letter* we report on much higher angular resolution VLBI observations of the Circinus X-1 radio source obtained during a major flare.

II. OBSERVATIONS AND DATA REDUCTION

The VLBI observations of Circinus X-1 were performed at 2.3 GHz during the period 1980 April 22–28. The 7 day observation span was chosen to coincide with a predicted radio flare, with the observations starting ~ 1 day before the expected flare initiation. Participating observatories were located at Tidbinbilla and Parkes in Australia and Hartebeesthoek in South Africa. Observations at Tidbinbilla were made at either the 64 m antenna (DSS 43) or the 34 m antenna (DSS 42), both of which achieved ~ 20 K system temperatures with traveling wave maser amplifiers. The 64 m antenna at Parkes was outfitted with a parametric amplifier to obtain a system temperature of ~ 110 K. At Hartebeesthoek, the 26 m antenna utilized a maser receiver yielding a system temperature of ~ 35 K. All observations were made with right circular polarization. A hydrogen maser frequency standard was used at Tidbinbilla, and rubidium standards were used at the other two sites.

The short baseline (Tidbinbilla to Parkes) provided a baseline length of 275 km (2.1×10^6 λ) with fringe spacings ranging from 0".10 to 0".29. The long baseline (Australia to South Africa) provided a baseline length of 9700 km (74×10^6 λ) with a nearly constant fringe spacing of ~ 0".003. The (u, v)-tracks for both the short and long baselines are shown in Figure 1. On the short baseline, nearly complete (u, v)-tracks (maximum of ~ 11 hours) were obtained on 4 days (April 22, 23, 24, 27), while significantly shorter tracks (~ 4 hours) were obtained on the other 3 days. On the long baseline, nearly complete (u, v)-tracks (maximum ~ 8 hours) were obtained on all days. In general, 10 minute VLBI observations of Circinus X-1 were made at average intervals of 45 minutes. In addition, frequent observations of calibration sources certain to produce strong fringes were made to check system performance.

Throughout the radio flare, total flux density measurements at 2.3 GHz were made at the Tidbinbilla 64 m antenna with the measurements usually preceding each VLBI observation. Since the beamwidth of this antenna at 2.3 GHz is 8'.4, the total flux density measurements included both the flaring and extended components of Circinus X-1.

A 1.8 MHz bandwidth was digitally sampled with the Mark II VLBI recording system (Clark 1973). Correlation coefficients were obtained from the VLBI data by use of the Caltech/JPL Mark II correlator and post-processing programs. Correlated flux densities were calculated by multiplying each correlation coefficient by a constant b ($b = 2.6 \pm 0.2$, Niell 1980), by the geometric mean of the antenna sensitivities (Jy/K), and by the geometric mean of the system temperatures. The 5 σ VLBI detection limits were about 20–40 mJy for each 10 minute coherent integration on both the long and short baselines. Correspondingly, the random uncertainty in each measured correlated flux density was about 4–8 mJy. However, correlated flux density errors were dominated by systematic effects at about the 10% level. Uncertainties in total flux density measurements were generally about 30 mJy.

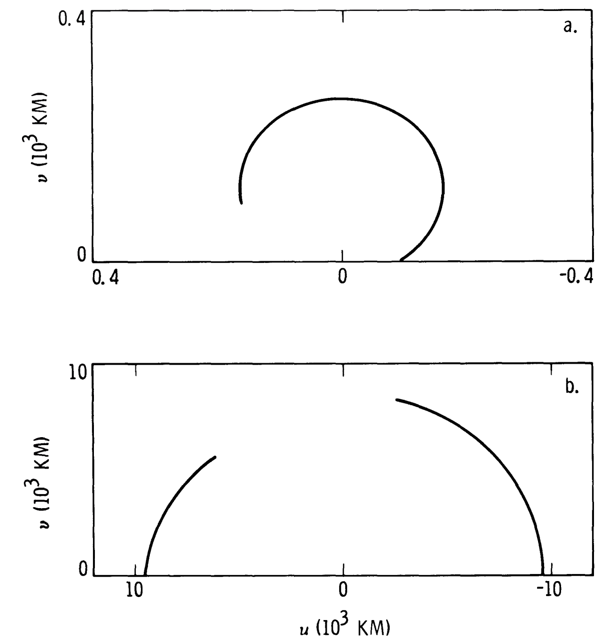

FIG. 1.—(u, v) tracks for Circinus X-1 on (*a*) Parkes/Tidbinbilla and (*b*) Tidbinbilla/Hartebeesthoek baselines.

III. RESULTS

Figure 2 shows the measured correlated flux density history of Circinus X-1 on the Parkes/Tidbinbilla baseline during the 7 days of observations. The total flux density history of Circinus X-1 during this time period is also plotted in Figure 2. The total flux density of the quiescent phase of Circinus X-1 (i.e., prior to flare initiation) was 0.27 ± 0.04 Jy. The onset of the radio flare occurred at about 14.8 ± 0.5 hours UT on April 23. The time of onset was estimated by using the detected values of correlated flux density on the Parkes/Tidbinbilla baseline on April 23, and linearly extrapolating backward in time to zero flux. The Circinus X-1 total flux density rose to a maximum of 1.5 Jy in ~ 30 hours and then decayed more slowly in an approximately exponential manner during the final ~ 95 hours of observation, reaching a value of 0.4 Jy at 20 hours UT on April 28.

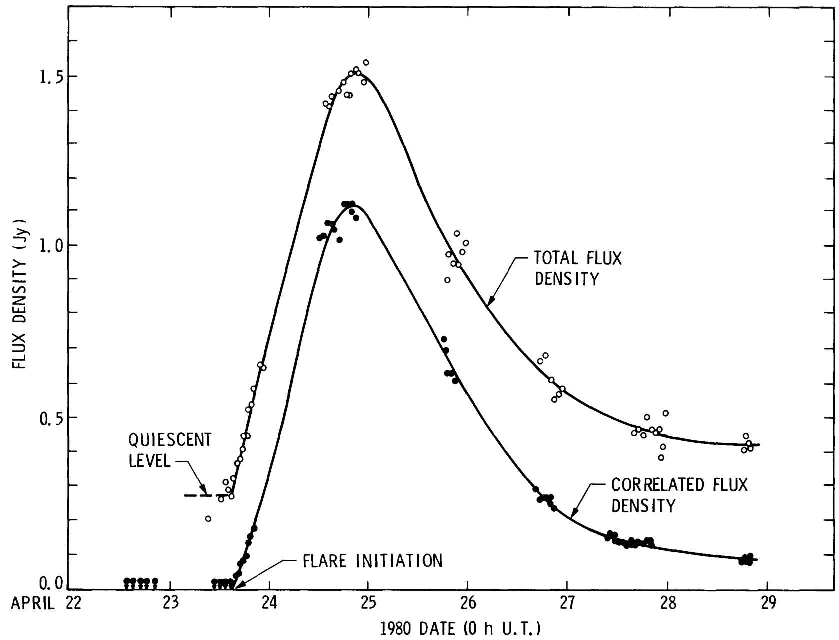

FIG. 2.—Correlated flux density history for Parkes/Tidbinbilla baseline plotted with total flux density history. Arrows indicate upper limits.

Preceding the flare, the quiescent component of the source showed no correlated flux density ($5\ \sigma \sim 20$ mJy) on the Tidbinbilla/Parkes baseline. From the time of flare initiation to the end of our observing period, the correlated flux density on this baseline matched the increase in total flux density over the quiescent level to within our observational errors. Hence, the quiescent component of the source was totally resolved, while the flaring component was totally unresolved on this baseline. No reliable detection of correlated flux density was made ($5\ \sigma \sim 40$ mJy) on the Australia/South Africa baseline during the observations.

IV. DISCUSSION

a) *Flaring Component*

The onset of the 2.3 GHz radio flare occurred about 2 hours later than the expected start of the radio flare at 5 GHz as predicted by two radio ephemerides of Nicolson (1980) which assume period changes in the source of -0.0036 and -0.0053 days per year. We note that the multifrequency radio observations of Haynes *et al.* (1978) hint that the time of onset of radio flares is not very frequency dependent between 2.3 and 8.4 GHz, but show that radio flares have smoother histories and more delayed peaks at the lower frequencies. The shape of the flare we observed is consistent with their 2.3 GHz results.

A strong, concurrent X-ray flare was observed with the *Hakucho* satellite (Hayakawa 1981). The X-ray flare began on April 23, about 5 hours prior to the radio flare onset and rose rapidly to an intensity in the 3–10 kev band of more than 10 times the preflare value. The X-ray flux then fell suddenly to the preflare level by about the time of the radio flare, peaked again several hours later, and finally decreased to the preflare level by April 26. Both the relative X-ray/radio phasing and the X-ray profile are unusual. This information might prove useful in future detailed modeling of the source.

The lack of detectable correlated flux density on the Australia/South Africa baseline indicates the source diameter is probably $\gtrsim 0.0015$ ($\gtrsim 15$ AU) throughout the flare history. The first observation on this baseline on the day the flare began occurred ~ 2.5 hours after the observed time of flare onset. From the rise time of a 15 GHz flare, Thomas *et al.* (1978) have deduced the size of the 15 GHz emission region to be less than 10 AU during flare onset. We note that a rapidly expanding source (e.g., a shell or jet) with a relativistic expansion velocity could possibly explain our nondetection on this baseline just after flare onset. A symmetric expansion velocity of $0.3c$ would allow a point object to grow to a size of 15 AU in ~ 3 hours. Since the observed total flux density of the flaring component was only 0.1 Jy after the flare was 3 hours old, we probably would not have detected (at $5\ \sigma$) a source that had already expanded to a size of 15 AU, or approximately one-half of our fringe spacing. Even if the expansion velocity were significantly less than $0.3c$, one might argue that radio emission could be delayed or self-absorbed until the source reached a size of ~ 15 AU. However, since the galactic latitude of Circinus X-1 is only 0°.04, a perhaps more likely explanation of our data is that the intrinsic source angular size is smaller than 0".0015, at least near flare onset, but that scattering by the interstellar medium causes the apparent source size to be larger than that value.

A failure to resolve the flaring component on the Tidbinbilla/Parkes baseline indicates that the source size probably was $\lesssim$ 0".015 ($\lesssim$ 150 AU) throughout the observing period. This limits the mean expansion velocity of a symmetrically expanding object to $\lesssim 0.1c$, if we assume the expansion started at a point at flare initiation. This low value of mean expansion velocity supports the hypothesis that the large apparent angular size at the start of the flare is due to interstellar scattering. The low expansion velocity is also consistent with the model for Circinus X-1 radio emission of Haynes, Lerche, and Murdin (1980) described previously, in which the expanding shock front would have reached a diameter of only 0.6 AU during our 125 hour observation of the flare.

b) *Quiescent Component*

The lack of detectable correlated flux density on the Tidbinbilla/Parkes baseline prior to the initiation of the flare indicates the diameter of the quiescent component is probably $\gtrsim$ 0".2 ($\gtrsim$ 2000 AU). This must represent an intrinsic rather than a scattered source size, since the flaring component was unresolved on this baseline. Hence, the quiescent radio emission is coming from a region much larger than the estimated 2 AU orbital dimensions of the binary system in the model proposed by Haynes *et al.* (1979). The large measured size of the quiescent component is probably inconsistent with the suggestion that the quiescent radio source is caused by leakage of relativistic electrons produced in an expanding shock front into an accretion disk surrounding the compact source.

Haynes *et al.* (1978) observed a quiescent 2.3 GHz total flux density of 0.51 ± 0.03 Jy prior to the 1977 May 12 flare, compared with our 2.3 GHz value of 0.27 ± 0.04 Jy measured prior to the 1980 April 23 flare. The quiescent component is clearly variable on a time scale of years and is most probably fueled in some way from the Circinus X-1 binary system. Measurements at 5 GHz (Haynes, Nicolson, and Jauncey, unpublished data) over the past 6 years confirm this flux density decrease. Time variability over 3 years is not inconsistent with our VLBI nondetection using fringe spacings of ~ 0".3, since an object 3 lt-yr in diameter at a distance of 10 kpc would subtend an angle of ~ 19" and would be totally resolved. The single antenna total flux density measurements indicate that the quiescent and flaring components are collocated to within ~ 1'. The possibility that the variable quiescent source is a background extragalactic source is not likely because of its close positional coincidence with the Circinus X-1 double star system and its rapid variability despite a large angular size.

The nature of the quiescent source is unclear, but the association of a large radio-emitting region with an active double star system is not unprecedented, for example, SS 433 and its associated extended component W50.

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