New radio observations of Circinus X-1

R. P. Fender

Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, UK

Abstract. New radio observations of the radio-jet X-ray binary Circinus X-1 over nearly an entire 16.6-day orbit are presented. The source continues to undergo radio flaring in the phase interval 0.0 – 0.2 and appears to be brightening since observations in the early 1990s. The radio flux density is well correlated with simultaneous soft X-ray monitoring from the XTE ASM, including a secondary flare event around phases 0.6 – 0.8 observed at both energies.

INTRODUCTION

Circinus X-1 is a highly unusual radio-bright southern X-ray binary. Every 16.6 days the source undergoes X-ray, infrared and radio outbursts (e.g. Glass 1994; Haynes et al. 1978). This is interpreted as heightened accretion during periastron passage of a compact object in an elliptical orbit around its companion star. There are few good spectroscopic observations due in part to the presence of two confusing sources within 2 arcsec of the optical counterpart (Moneti 1992), and the nature of the companion star remains uncertain.

Cir X-1 is embedded within a synchrotron nebula which trails back towards the nearby SNR G321.9-0.3. Synthesis mapping at 6 cm with ATCA has resolved jet-like structures within this nebula, originating at the location of the binary and curving back towards G321.9-0.3 (Stewart et al. 1993) – this suggests the source may be a runaway X-ray binary with an origin in the SNR. The radio brightness of the source at cm wavelengths declined significantly from the late 1970s to the early 1990s, with Haynes et al. (1978) recording flux densities in excess of 1 Jy, while Stewart et al. (1993) only measured a few mJy.

Here we present new radio monitoring of Cir X-1, over most of an orbital period, in 1996 July, including a comparison with simultaneous soft X-ray monitoring with the XTE ASM.
FIGURE 1. ATCA observations, simultaneously at 6.3 & 3.5 cm, of Cir X-1 between 1996 July 1 – 14. Orbital phase as calculated both by the linear ephemeris of Stewart et al. and the quadratic ephemeris of Nicolson is indicated – clearly the Nicolson ephemeris is more accurate. Flux density variations within a single observation are confused by resolution and $u$-$v$ effects, but the day-to-day variations are real and the source is clearly brightest in the phase interval 0.0 – 0.2. The spectral index, plotted in the lower panel, is consistent with nonthermal synchrotron emission.

OBSERVATIONS

Cir X-1 was observed with the Australia Telescope Compact Array (ATCA) on fourteen days of its 16.6 day orbit between 1996 July 1 – 14. Observations were made simultaneously at wavelengths of 6.3 & 3.5 cm, with the array in high
resolution 6D configuration (6 km maximum baseline). The effective resolution of
the array in this configuration is \( \sim 2 \) and \( \sim 1 \) arcsec at 6.3 \& 3.5 cm respectively.
The first two runs on Cir X-1 were of duration \( \sim 12 \) and \( \sim 10 \) hr respectively, in
order to map the source at high resolution. However, while there is some evidence
of jet-like structure in the resultant maps at both wavelengths, uncertainty as to
the contribution both from intrinsic source variability and the surrounding nebula
render such features unreliable. The lack of much of the synchrotron nebula in the
maps suggests that it is of relatively low surface brightness, with little structure on
small (few arcsec) angular scales.

RESULTS

The light curve

Fig 1 shows the radio light curve from Cir X-1 over the entire set of observations. As
described above, it is hard to differentiate intrinsic source variability from res-
olution and \( u-v \) coverage effects, and so apparent variability on short timescales
should not be taken too seriously without further careful analysis. However, the
large day-to-day changes, with a drop in flux density by a factor of \( \sim 3 \) are indeed
significant. The flux density of the source, at all phases, while well below that
reported in the 1970s, appears to have risen considerably since the observations of
Stewart et al. (1993) in the early 1990s.

The spectral index \( (\alpha = \Delta \log S_\nu / \Delta \log \nu) \) of the radio emission, plotted in the
lower panel of Fig 1, is consistent with optically thin synchrotron emission with \( \alpha \)
around -0.5.

A note on the ephemerides ..

Stewart et al. (1993) discuss two ephemerides for Cir X-1: a quadratic ephemeris
from Nicolson (private communication), and a simplified linear ephemeris of their
own. The orbital phase as calculated from both ephemerides is shown in Figure 1;
from this it is apparent that the linear ephemeris of Stewart et al. is in error in its
prediction of the time of outburst, and the Nicolson ephemeris must be considered
more reliable. However, given that the XTE ASM has by now observed more than
thirty periodic outbursts of the system, a newly refined X-ray ephemeris may be
called for.

Comparison with X-ray monitoring

Fig 2 compares the radio light curve at 6.3 cm with the 2-12 keV lightcurve
obtained by the XTE ASM. A clear correlation exists, with flaring activity in both
FIGURE 2. A comparison of the ATCA 6.3 cm light curve with simultaneous soft X-ray monitoring with the XTE ASM. The activity in the two bands is clearly correlated at all phases. The major flaring, presumably occurring around the time of periastron passage of the compact object, is obvious. Note also however, the secondary flaring, both in X-rays and radio emission, around phase 0.6 – 0.8.

energy regimes occurring between phases 0.0 – 0.2 followed by a subsequent decline. This supports the picture of some enhanced accretion and related particle acceleration/ejection occurring around the time of periastron passage.

Note also the lesser flaring, again at both energies, in the phase interval 0.6 – 0.8 (near apastron). Such a secondary radio outburst half an orbit after the primary flare has not previously been reported.
CONCLUSIONS

Cir X-1 has been observed over most of its 16.6-day orbit simultaneously at 6.3 & 3.5 cm, and in the 2-12 keV energy range with the XTE ASM. The source is clearly continuing to undergo radio flaring around phase 0.0 – 0.2 (from the quadratic ephemeris of Nicolson), and may have begun brightening since observations in the early 1990s. There is also a clear coupling between the soft X-ray activity (reflecting the state of the accretion process) and the radio brightness (probably reflecting the ejection of synchrotron-emitting material). In addition, secondary radio flaring around phases 0.6 – 0.8, which is correlated with the X-ray behaviour, has been discovered.

Cir X-1 is the only X-ray binary for which there is both strong evidence for radio jets and direct evidence that the compact object is a neutron star (from Type I X-ray bursts). It is a key system in our understanding of radio emission, in particular jets, from X-ray binaries. Future radio observations, including flux monitoring, mapping and accurate proper motion measurements, will be of great importance.

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