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Nature of Circinus X-1

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Abstract

X-ray, radio and optical observations have been used to derive a binary star model for Circinus X-1. Mass transfer between the primary star ($M_p \approx 20\,M_\odot$) and the compact companion star ($M_c \approx M_\odot$) triggers one or more expanding shock fronts in the vicinity of the compact star. These shocks produce the observed radio emission. Variable optical emission arises both from the changing Roche lobe surface in the highly eccentric system ($e \approx 0\cdot8$) and from degradation of shock-produced X-ray photons to the optical band by material overlying the expanding shock. The X-ray radiation results from matter in the accretion disc dribbling down on to the surface of the compact star. Mass replenishment at a rate of 5×10^{-8} to $5\times10^{-10}\,M_\odot$ per orbit (16·6 day period) occurs near periastron passage. The variation of the X-ray emission arises from absorption in the stellar wind of the primary star. The model predicts an apsidal rotation period for the elliptical orbit of 7–400 yr, an orbital circularization time of $\sim$500 yr and a period change of about 0·5 day per 10 yr.

Introduction

Circinus X-1 most sharply delineates the physical processes occurring in X-ray binary systems. By collating data covering a wide range of the electromagnetic spectrum we have produced a comprehensive theoretical picture which accounts for *all* of the currently available information. In order to encourage further observations, the main points of our theoretical explanation are given here. In particular, we concentrate on the major phenomena seen in the radio band, which have yielded significant insight into the behaviour of Circinus X-1. A full explanation of all of the X-ray, optical and radio data is presented elsewhere (Haynes *et al.* 1978*b*). The model predicts effects which should be observable over the next few years.

Discussion

X-ray, optical and radio data (Forman *et al.* 1976; Kaluzienski *et al.* 1976; Coe *et al.* 1977; Glass 1977*a*, 1977*b*; Goss and Mebold 1977; Kaluzienski and Holt 1977; Whelan *et al.* 1977; Haynes *et al.* 1978*a*, 1978*c*) (Fig. 1) indicate that Cir X-1 is a binary star system 10 kpc distant (Webster 1974; Goss and Mebold 1977) with a period of 16·595 days and an orbital eccentricity $e \approx 0\cdot72$. To explain the observed radio bursts from Cir X-1 we suppose that Roche lobe overflow from the primary star occurs only around periastron, triggering at least one expanding luminosity-driven shock from the compact star's surface (Haynes *et al.* 1978*b*). Synchrotron radiation from energetic electrons at the shock front is sufficient to account for the temporal and frequency structure of the radio outbursts (Haynes *et al.* 1978*b*). The increased optical emission (Glass 1977*a*, 1977*b*; Haynes *et al.* 1978*c*) seen simultaneously with the radio bursts seems to be accounted for by the increased Roche lobe surface area near periastron (Haynes *et al.* 1978*b*). The drop in X-ray emission at this phase is caused by absorption of the X-rays in the strong stellar wind of the primary OB supergiant.

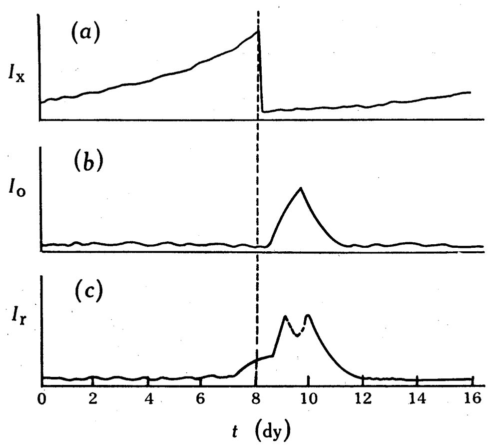

Fig. 1. Sketch of the periodic emission intensity I from Cir X-1 at (*a*) X-ray (1976–77), (*b*) optical (1977) and (*c*) long radio (1977) wavelengths. The location of the X-ray cutoff transition is indicated by the dashed line.

Fig. 1 shows the behaviour of the X-ray, optical and radio emission throughout one orbital period. Measurements of the periodic radio flares (Clark *et al.* 1975; Whelan *et al.* 1977; Haynes *et al.* 1978*a*, 1978*c*) indicate the following general characteristics of the radio bursts:

(i) The flaring radio source is a point source ($\lesssim 40''$ arc diameter) coincident in position with both an early-type emission line star and the X-ray source (Whelan *et al.* 1977; Haynes *et al.* 1978*c*).

(ii) High-frequency radio flares, of peak flux density ~ 2 Jy at 14 GHz, are often double-humped, and always occur after the X-ray cutoff (Haynes *et al.* 1978*c*). Humps are typically ~ 10 h wide and separated by ~ 18 h.

(iii) In the steep part of the radio flare spectrum (Haynes *et al.* 1978*c*) the flux density is $S(\nu) \propto \nu^{5/2}$, which argues for an optically thick synchrotron emitter with a power-law distribution of electron energy. At periastron, optical depth unity occurs around 1 GHz (Whelan *et al.* 1977; Haynes *et al.* 1978*c*).

(iv) The time lag Δt from X-ray cutoff to the first peak of the radio flare at frequency ν satisfies (Haynes *et al.* 1978*c*) $\Delta t \propto \nu^{-0.8 \pm 0.1}$.

(v) The radio flare intensity of first maxima satisfies (Haynes *et al.* 1978*c*) $S_{\max}(\nu) \propto \nu^{1.0 \pm 0.2}$.

(vi) The radio spectrum of the quiescent source satisfies (Haynes *et al.* 1978*c*) $S(\nu) = 0 \cdot 3(\nu/5)^{-0.5 \pm 0.05}$ Jy, with ν in gigahertz.

Consider now the theory: To explain the rapidity of the drop in X-ray emission ($\lesssim 0 \cdot 1$ day) (Carruthers 1968; Watson *et al.* 1976; Dower *et al.* 1977; Kaluzienski and Holt 1977) by absorption in the stellar wind requires (Haynes *et al.* 1978*c*) $e \approx 0 \cdot 8$. The pre-flare increase in the 5 GHz radio flux is attributed to mass accretion from the primary star's stellar wind (Haynes *et al.* 1978*a*) and this yields a similar value of $e = 0 \cdot 72 \pm 0 \cdot 01$. The primary star is probably (Clark *et al.* 1975; Coe *et al.* 1977; Glass 1977*a*, 1977*b*) a massive ($M_p \approx 20\, M_\odot$) OB supergiant losing mass at a rate (Morton 1967, 1969; Lucy and Solomon 1970; Ostriker and Davidson 1973) of about $10^{-6} M_{\odot}\,\mathrm{yr}^{-1}$ via a strong stellar wind. The companion star is probably a compact star (Clark *et al.* 1975; Coe *et al.* 1977; Glass 1977*a*, 1977*b*) ($M_c \approx M_{\odot}$), most likely a neutron star.

From the above masses and the period, the semimajor axis of the orbit is ~ 1 A.U. With $e \approx 0{\cdot}8$, the apastron and periastron distances are ~ 2 and $\sim 0{\cdot}1$ A.U. respectively; in this case, physical processes that are essentially 'steady' in low-eccentricity X-ray binary objects become highly dependent on the orbital positions of the stars. The compact star (radius $\sim 10^6$ cm) approaches within $\sim 10^{12}$ cm of the surface of the primary star (radius $\sim 1{\cdot}5 \times 10^{12}$ cm) during periastron passage, which lasts about 3 days. During this time, the mass transfer due to Roche lobe overflow from the supergiant exceeds (Pringle and Rees 1972; Ostriker and Davidson 1973; Shakura and Sunyaev 1973) $10^{-8} M_{\odot}\,\mathrm{yr}^{-1}$, the Eddington limit for a 1 $M_{\odot}$ compact star. On impact at the surface of the compact star a flux of high-energy photons ($\sim 10^{38}\,\mathrm{erg\,s^{-1}}$) is generated in a time much less (Pringle and Rees 1972; Shakura and Sunyaev 1973) than the free-fall time ($\sim 10^4$ s). Radiation pressure pushes outward on the infalling material (whose density varies as $\sim r^{-3/2}$, with r measured from the compact star). This creates (Haynes *et al.* 1978*b*) an impulsively driven shock wave whose radius at time $t(s)$ after formation is given (Haynes *et al.* 1978*b*) by $R_{\mathrm{shk}} \approx 3 \times 10^9\, t^{4/7}$ cm. The shock thickness in terms of the Compton time constant τ_c is (Haynes *et al.* 1978*b*) $c\tau_c \approx 3 \times 10^6$ cm.

The ion–electron collision time is about 10^{-2} s, approximately independent of distance from the compact star, so that the electrons rapidly reach the ion temperature. The electrons are then relativistic, with $\gamma \equiv kT_e/m_e c^2 \approx 3 \times 10^2$. From the observed flux density (2 Jy at 14 GHz) the radio brightness temperature at wavelength λ (cm) is $T_B \approx 10^{13}\lambda^2(10^{11}/d)^2$ K, where d (cm) is the size of the emitting region, which we take to be R_{shk}. To account for the observed radio brightness, electron energies corresponding to $\gamma \approx 10^3$–10^5 are therefore necessary. Bell's (1978) mechanism for rapid acceleration of charged particles at shock fronts appears appropriate for Cir X-1, providing an efficient way of boosting already energetic electrons to the required energy without straining the overall energy budget. The mechanism produces an electron energy distribution $\propto E^{-\Gamma}$ ($\Gamma \approx 2$) which can be maintained for approximately one collision mean-free-path ($\sim 3 \times 10^8$ cm) ahead of the shock. Synchrotron radiation is produced at the shock front in the compressed magnetic field of the supergiant. (The field is, of course, 'frozen-in' to the material infalling through the Roche lobe.) The X-ray component is absorbed in the stellar wind; any optical component (Shakura and Sunyaev 1973) just adds to optical emission arising from the increased Roche lobe surface area near periastron. However, in the radio band, synchrotron self-absorption effectively 'blocks' radiation until the shock wave expands to the point where the material becomes transparent. Following van der Laan's (1966) argument, the radio flare is then to be seen first at the highest frequencies. With the maximum of the spectral curve at frequency ν_1 at time t_1, the maximum reaches ν_2 at time t_2, where (Haynes *et al.* 1978*b*)

$$t_2/t_1 = (\nu_1/\nu_2)^{7(\Gamma+4)/4(4\Gamma+6)}$$

and

$$S_{\max}(t_2)/S_{\max}(t_1) = (t_2/t_1)^{-4(7\Gamma+3)/7(\Gamma+4)}$$
$$= (\nu_2/\nu_1)^{(7\Gamma+3)/2(2\Gamma+3)}.$$

The change of spectral shape with time gives the time lag

$$\Delta t \propto \nu^{-m},$$

where

$$m = 7(\Gamma+4)/4(4\Gamma+6) = 0\cdot 75 \qquad \text{for} \qquad \Gamma = 2.$$

Thus we have

$$S_{\max}(\nu) \propto \nu^{n},$$

with

$$n = (7\Gamma+3)/2(2\Gamma+3) \approx 1\cdot 2 \qquad \text{for} \qquad \Gamma = 2.$$

Observations (Haynes *et al.* 1978*c*) give $m \approx 0\cdot 8$ and $n \approx 1$, based on the first maxima at 8 and 5 GHz (see points (iv) and (v) above). In the optically thick radio regime, the theory (Haynes *et al.* 1978*b*) gives $S(\nu) \propto \nu^{5/2}$, as is observed (Forman *et al.* 1976; see point (iii) above).

The dynamical pressure of the OB supergiant's stellar wind exceeds (Haynes *et al.* 1978*b*) the shock wave pressure when $R_{\rm shk} \gtrsim 10^{12}$ cm, that is, at about 2×10^{4} s after shock wave formation. The shock then dissipates in the stellar wind. The duration of Roche lobe overflow near periastron passage is, however, about 10^{5} s, so that there is ample time for more than one such shock to form. This explains the usually observed (Whelan *et al.* 1977; Haynes *et al.* 1978*a*, 1978*c*) double-humped high-frequency radio flares.

An accretion disc forms around the compact star as in the standard Roche picture of *steady* binary mass transfer (Prendergast and Burbidge 1968; Schwartzman 1971; Pringle and Rees 1972; Shakura and Sunyaev 1973). As the disc's angular momentum dissipates (Shakura and Sunyaev 1973; Watson *et al.* 1976) mass drains out of the disc onto the compact star, producing a steady X-ray luminosity of 10^{35}–10^{38} erg s^{-1}. The stellar wind of the OB star prevents the escape of this radiation near periastron. At this time the disc is also replenished, with a mass estimated (Haynes *et al.* 1978*b*) at $\sim 5\times 10^{-8}$ to $5\times 10^{-10}\,M_{\odot}$ being supplied per orbit. Some of the relativistic electrons produced in the shock leak into the accretion disc, giving rise, by optically thin synchrotron emission, to a steady radio output when the compact star is far from periastron. The frequency dependence is then $\nu^{-0\cdot 5}$, corresponding to $\Gamma = 2$, as observed (Whelan *et al.* 1977; Haynes *et al.* 1978*c*). This accounts for the quiescent radio emission.

Near periastron the supergiant's stellar wind has a plasma frequency $\nu_{\rm p}$ that is high enough to suppress emission at $\nu \lesssim 1$ GHz but not to affect emission at $\nu \approx 1\cdot 4$ GHz. As the compact star departs from periastron $\nu_{\rm p}$ decreases as $r_{\rm sep}^{-1}$, where $r_{\rm sep}$ is the separation between the supergiant and the compact star. Lower-frequency radio emission can then transit the stellar wind, as observed (Whelan *et al.* 1977; Haynes *et al.* 1978*c*).

The compact star steadily picks up mass from the supergiant's stellar wind, resulting in a component of radio luminosity $\propto r_{\rm sep}^{-2}$. This effect (Haynes *et al.* 1978*b*) was recently observed and used to derive an eccentricity $e \approx 0\cdot 72\pm 0\cdot 01$ (Haynes *et al.* 1978*a*).

Predictions of the theory are:

(1) Tidal forces cause precession of the line of apsides of the orbit with a period which is estimated (Haynes *et al.* 1978*b*) to be between 7 and 400 yr. Both the *shape* of the X-ray light curve and the observed *time* between the rapid

drops in the X-ray light curve are affected by the precession. An apsidal rotation period of some 10 yr is indicated, based on ascribing (*a*) the eclipse-like X-ray light curve seen by Uhuru in 1971–72 to an orientation of the orbit in which periastron of the compact star is behind the primary; (*b*) the short duty-cycle pulse (Kaluzienski *et al.* 1976) of 1976 to an orientation in which periastron is this side of the primary. On this ascription, Haynes *et al.* (1978*b*) have predicted that the phase of the X-ray emission will follow the line of apsides and that the X-ray light curve will return to the eclipse-like state in 1981–82.

(2) The mass loss of the OB supergiant and the consequent mass gain of the compact star argue for circularization of the orbit (Sterne 1939; Kopal 1959) in a time (Haynes *et al.* 1978*b*) of about 500 yr. Haynes *et al.* (1978*b*) have predicted that, as the orbit circularizes, the period should change by about 0·5 day every 10 yr and that, as circularization proceeds, the periastron distance between the compact star and the supergiant increases. Less mass overflow then occurs, so that, apart from short-term fluctuations, a steady diminution in the flaring output of Cir X-1 at a rate of about 0·2% yr^{-1} is predicted. We also note that less mass replenishment of the accretion disc occurs, so that it is expected that the steady X-ray and radio luminosities will also show a systematic decrease with time at a similar rate.

(3) Tidal interaction theory (Sterne 1939; Kopal 1959) also argues for a libration of the plane of the orbit. There is a faint suggestion in recent data (Haynes *et al.* 1978*a*) that we are starting to see effects directly attributable to the libration. Unfortunately, there is not yet adequate coverage of a sufficient number of flares to determine convincingly either the period or amplitude of the orbital libration. These must await further observations.

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