Astron. Astrophys. 323, 876–880 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Particle injection in the Circinus X-1 radio outbursts

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Received 17 June 1996 / Accepted 14 January 1997

Abstract. A particle injection model has been applied to the radio outbursts of the X-ray binary Circinus X-1. The radio outbursts of this system have often been observed to exhibit a double peaked structure, i.e., with two apparent consecutive maxima. We show here that particle injection models can account for such observed behaviour provided that a time variable particle injection rate is adopted. Several possible time dependences are assumed and the corresponding predicted radio light curves compared with multi-frequency observations collected from the literature.

Key words: stars: individual: Cir X-1 – radio continuum: stars – X-rays: stars

1. Introduction

Cir X-1 is the only X-ray binary with periodic radio emission known in the Southern Hemisphere. It was first detected as an X-ray source by Margon et al. (1971) and observations of type I X-ray bursts by Tennant et al. (1986) established that the compact object is a neutron star. Periodic occurrences of abrupt changes in the X-ray light curves accompanied by radio flares seem to imply an eccentric binary system with an orbital period of 16.6 d (Kaluzienski et al. 1976; Whelan et al. 1977).

The optical counterpart of Cir X-1 is a faint red star (Moneti 1992) located in a highly obscured region at a distance of 6-10 kpc (Goss & Mebold 1977; Stewart et al. 1991).

The radio intensity of the periodic flares has dropped since the 1980's, in parallel with changes of the X-ray light curves. Orbital precession of the binary system, as first suggested by Murdin et al. (1980), could explain this behaviour. A 843-MHz map by Haynes et al. (1986) reveals the presence of a radio synchrotron nebula surrounding Cir X-1, possibly as a consequence of accumulated energetic electrons ejected during the radio outbursts. From VLBI observations of the Cir X-1 radio source during a major flare, Preston et al. (1983) estimate the mean expansion velocity of the flaring component to be ≤ 0.1 c and an angular size of few milliarcseconds. The possible presence of extended radio jets has been reported by Stewart et al. (1993).

The periodic radio flares are thought to be the consequence of enhanced accretion onto the compact star near the time of periastron passage (Haynes et al. 1980). These authors interpreted the flaring radio behaviour of Cir X-1 as a result of expanding luminosity-driven shocks due to a mass transfer onto the compact companion in excess of the Eddington accretion rate. Different radio flaring events, such as those observed by Whelan et al. (1977) and Haynes et al. (1978), have usually displayed what seems to be a double-peaked structure. The presence of two peaks in the shape of the radio light curve has been observed as well in the similar radio periodic X-ray binary system LSI+61°303 (Taylor et al. 1992; Ray et al. 1996).

In this paper we apply a particle injection model, with different time-dependent particle injection rates, in order to reproduce one of the double peaked Cir X-1 radio outbursts that was extensively observed by Haynes et al. (1978). The mechanism of particle injection has been previously applied to other X-ray binaries such as LSI+61°303 (Paredes et al. 1991), Cyg X-3 (Peterson 1973; Martí et al. 1992) and SS433 (Martí 1993).

2. The model

Our model is an adapted version of the one developed in Paredes et al. (1991) for LSI+61°303, with the main differences being the assumption here of spherical geometry and, more important, a time variable particle injection rate.

We assume that a radio outburst can be modelled as the ejection of an expanding spherical cloud (plasmon), of radius r, containing a uniform distribution of synchrotron-emitting relativistic electrons and magnetic fields, following a transitory supercritical accretion event onto the compact star. Fresh relativistic electrons are continuously injected into the plasmon, which is in adiabatic expansion at a constant velocity $v_{\rm exp}$. In the course of the expansion the electrons are subjected to adiabatic and synchrotron energy losses. The magnetic field has an average value B that we determine assuming magnetic flux conservation ($B \propto r^{-2}$).

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The flux density for each frequency can be expressed as:

$$S_\nu = \pi \left(\frac{r}{D}\right)^2 \frac{\epsilon_\nu}{\kappa_\nu} \left(1 - e^{-\tau'_\nu}\right) \xi_{\rm sph}(\tau'_\nu), \quad (1)$$

where ϵ_ν and κ_ν are the total emission and absorption coefficients, $\tau'_\nu \equiv 2r\kappa_\nu$ is the optical depth through the central line of sight, D is the distance to the radio source and $\xi_{\rm sph}(\tau'_\nu)$ is a geometrical correction factor (Hjellming & Johnston 1988). In the model application by Paredes et al. (1991), a cylindrical geometry was considered with lines of sight all of the same length across the plasmon. However, by using the above geometrical correction factor it is easy to account for the spherical geometry and we adopt this approach in our model.

In Eq. (1), the total emission and absorption coefficients are computed by numerical integration using the corresponding integral expression from synchrotron radiation theory (Pacholczyk 1970). The main dependence is on the source injection term $Q(E, \rho)$, which gives the number of relativistic particles injected per unit energy interval and per unit time. We refer the reader to Paredes et al. (1991) for details. Assuming an energy power law spectrum of index p, as is usual for synchrotron radio sources, with energy limits $E_{\rm d} \leq E \leq E_{\rm u}$, the source term can be written as:

$$Q(E, \rho) = Q_{\rm o} f(\rho) E^{-p} \quad (2)$$

with $Q_{\rm o}$ being a normalization constant and $f(\rho)$ the time dependence of the source term. The nondimensional variable $\rho \equiv \frac{r}{r_{\rm o}}$ has been used here instead of time to simplify the notation.

In what follows two different forms will be considered for the possible time dependence of the function $f(\rho)$, namely, a time variable and a constant form.

2.1. Variable particle injection

The time dependence of the injection process could be especially important for binary systems where the accretion rate $\dot{M}_{\rm acc}$ changes significantly along the orbital phase. If the accretion is of the Bondi (1952) type, we have in particular:

$$\dot{M}_{\rm acc} = \frac{4\pi (G M_{\rm c})^2 \rho_{\rm w}}{v_{\rm rel}^3} \quad (3)$$

where $M_{\rm c}$ is the mass of the compact star, $\rho_{\rm w}$ the stellar wind density at the compact star position and $v_{\rm rel}$ the relative velocity between the stellar wind and the compact star. In this case and for orbits of high eccentricity, it can be shown that $\dot{M}_{\rm acc}$ interestingly exhibits two well defined maxima when computed along the orbit (Taylor et al. 1992). The first one corresponds to periastron passage, when the compact star moves through the densest parts of the stellar wind. The second maximum takes place for orbital positions, after periastron passage, in which the relative velocity $v_{\rm rel}$ is low enough to compensate for the stellar wind density decrease. Both accretion rate maxima or peaks may reach super Eddington levels for suitable combinations of orbital and stellar wind parameters. Therefore, since we are looking for double-peaked radio light curves, it appears natural to consider whether these two $\dot{M}_{\rm acc}$ maxima could be related in some way to the double peaked radio outbursts in Cir X-1.

In order to better test this idea, we assume here that the time dependence $f(\rho)$ of the source term $Q(E, \rho)$ is just proportional to the accretion rate excess over the Eddington limit, whenever this is exceeded, and zero otherwise. Written in a normalized form:

$$f(\rho) = \begin{cases} \eta(X - 1) & X > 1 \\ 0 & X \leq 1 \end{cases} \quad (4)$$

where $\eta \leq 1$ is an efficiency factor and $X \equiv \dot{M}_{\rm acc}/\dot{M}_{\rm Edd}$ has been defined. Note that in these expressions the time dependence is included in X, which is actually a function of the orbital phase, and the duration of the particle injection process is given by the time interval in which $X > 1$. Finally, for the stellar wind or circumstellar envelope of the donor companion star, we assume here a simple power law density $\rho_{\rm w} \propto \dot{M}_{\rm w} r^{-{\rm n}}$ and velocity $v_{\rm w} \propto \dot{M}_{\rm w} r^{{\rm n}-2}$ distribution (Waters et al. 1988), where $\dot{M}_{\rm w}$ is the companion total mass loss rate.

2.2. Constant particle injection

It is also straightforward to consider a constant particle injection rate into the spherical plasmon just by setting $f(\rho) = 1$ during a finite time interval $0 \leq t \leq t_{\rm f}$ and zero afterwards. However, this simple dependence always produces a single maximum in the radio light curves. So, for a constant particle injection rate, it is necessary to assume two consecutive plasmon ejections in order to obtain a double peaked radio light curve. An additional complication also arises here because one has to take carefully into account the overlapping emission contributions from both plasmons.

3. Application of the model and results

The only data published up to now of simultaneous multifrequency observations of a radio outburst of Cir X-1 are those by Haynes et al. (1978), at 1.4, 2.3, 5.0 and 8.4 GHz between 12-15 May 1977. These data reveal a double peaked structure particularly at 5.0 and 8.4 GHz, with peaks separated by about 1 day, while at 1.4 and 2.3 GHz it does not seem to be more than a single broad peak. In its quiescent state, the radio spectrum may be well approximated as $S_\nu \propto \nu^{-0.5}$ (Haynes et al. 1978).

The model described above has been applied to these four-frequency simultaneous observations after removing the quiescent spectrum from all the data points. A lower limit of $E_{\rm d} \sim 10^{-6}$erg and an upper limit of $E_{\rm u} \sim 10^{-2}$erg have been adopted for the power law relativistic electron energy spectrum. The model does not depend strongly on these values. A distance of 8.5 kpc has been assumed. Inverse Compton losses are not taken into account because, assuming typical values for the photon energy density of the faint primary star, inverse Compton scattering by relativistic electrons does not significantly contribute to the energy losses.

Table 1. Physical parameters for variable particle injection

Initial radius (cm)	2.2×10^{13}
Initial magnetic field (G)	4.7
Expansion velocity (cm s^{-1})	5.5×10^{8}
Power law index, p	1.4
Initial injection date (May 1977)	11.94

3.1. Application of variable particle injection

We intend here to reproduce the double peaked radio light curves of Cir X-1 by means of a single plasmon ejection in which the particle injection rate is controlled by the shape of the accretion curve as given by Eq. 3.

Some of the system parameters are adopted a priori and kept fixed at standard values throughout the modelling. These include a binary system eccentricity e = 0.8 (Murdin et al. 1980) and a compact star with a canonical mass and radius of 1.4 $M_\odot$ and 10 km, respectively. For the other less certain parameters, a grid of different ranges of plausible values has been considered (the mass of the primary star M_* = $1-15$ $M_\odot$, the mass loss rate of the primary star $\dot{M}_{\rm w} \sim 10^{-7} - 10^{-8}$ $M_\odot$ yr^{-1}, the initial wind velocity at the surface of the primary star $v_{\rm w*}$ = $5-25$ km s^{-1} and the index n = $2.5-3.5$). Suitable parameter combinations have been further narrowed by systematically inspecting which ones actually produce accretion curves with two clear super-critical maxima. Whenever this is detected, a parameter search, within reasonable physical limits, is made to fit the remaining plasmon parameters, i.e., the initial radius of the plasmon $r_{\rm o}$, the initial magnetic field $B_{\rm o}$, the expansion velocity of the plasmon $v_{\rm exp}$, the power law index p and the initial injection date. Unfortunately, the problem is not well constrained and a clearly unique solution is not easy to find. Nevertheless, we list in Table 1 a representative example of the physical parameters for the best fit solutions found. Varying these parameters by 10-20 % still produces roughly acceptable fits. The corresponding radio light curves are shown in Fig. 1 together with the data from Haynes et al. (1978).

The curves here were obtained by considering a primary star of mass M_* = 8 $M_\odot$, $\dot{M}_{\rm w}$ = 1.65×10^{-7} $M_\odot$ yr^{-1}, $v_{\rm w*}$ = 23.1 km s^{-1}, n = 2.96 and an efficiency factor in producing relativistic electrons of η = 0.18. For these same values, Fig. 2 plots the resultant accretion rate curve, in units of the Eddington accretion limit (dashed line), against arbitrary orbital phase. For a fraction of the orbital period, the accretion increases above the Eddington limit with two clear maxima.

The model with variable particle injection rate fits the data at each frequency reasonably well. The total mass of injected relativistic particles amounts to 6.9×10^{-14} $M_\odot$, 2.4 days being the total injection time interval.

The resulting efficiency factor exceeds what would be expected. However, a similar problem is found, e.g., in GRS 1915+105, where the mass of relativistic particles injected into the jets must be a large fraction of the total mass accreted by the compact object (Mirabel & Rodríguez 1995). In this way, Cir X-1 would not be a unique case in requiring such a high efficiency, although the physical mechanism to achieve it remains uncertain.

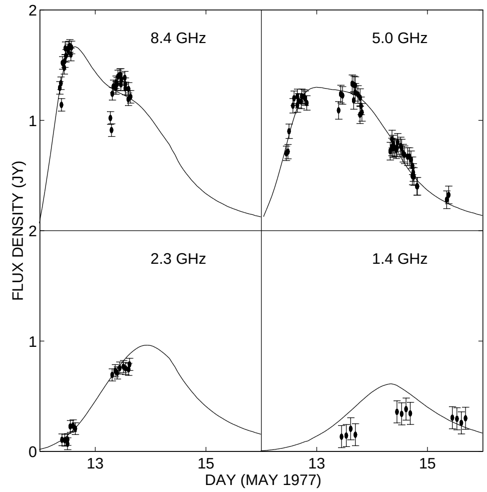

Fig. 1. Data from Haynes et al. (1978) of the 12-15 May 1977 radio outburst compared with the radio light curves computed from our model for a variable particle injection rate.

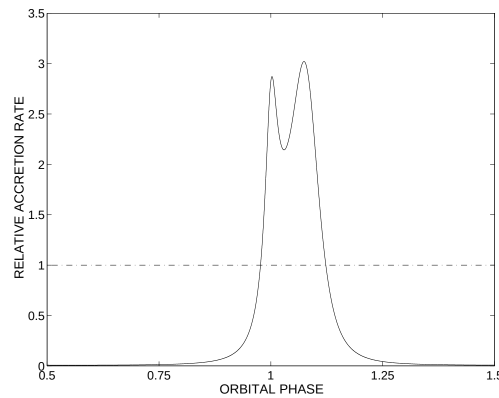

Fig. 2. Accretion curve via stellar wind of Cir X-1 using the best fit parameters and eccentricity e = 0.8, as a function of an arbitrary orbital phase. The vertical axis is in units of the Eddington accretion limit (indicated by the dashed line).

The initial magnetic field strength of a few gauss considered requires a process for generating the magnetic field in which the field is frozen inside the plasma and dragged by the latter as the plasma cloud expands. From the parameters describing the stellar wind it can be inferred that the magnetic pressure of the plasmon is roughly balanced by the stellar wind pressure up to distances of the order of the semimajor axis value. Therefore, it is conceivable that the plasmon remains contained facing the stellar wind pressure and its expansion outwards can only take place outside the orbital volume.

Table 2. Physical parameters for constant particle injection

Initial injection date (May 1977)	12.25	13.15
Initial radius (cm)	1.4×10^{13}	1.4×10^{13}
Initial magnetic field (G)	1.9	1.4
Expansion velocity (cm s^{-1})	8.8×10^{8}	6.0×10^{8}
Power law index, p	1.5	1.6
Injection rate ($M_{\odot}$ d^{-1})	6.8×10^{-14}	6.4×10^{-14}
Injection time interval (d)	1.1	2.2

3.2. *Application of constant particle injection*

In this case we consider the ejection of two plasmons separated by a time interval of about one day. The computed radio light curves take into account the overlapping of both plasmons. No specific mechanism of accretion onto the compact star is assumed here, so we must add the injection rate and the injection time interval to the set of parameters to be fitted. As before, the problem is not well constrained and different sets of parameters can give equivalently good fits.

A representative set of values obtained for the physical parameters of the fit are listed in Table 2, and Fig. 3 shows the radio light curves computed together with the data from Haynes et al. (1978). The shape, peak flux density and time delay of the peaks at the three higher frequencies are again acceptably well reproduced, although the outburst at 1.4 GHz is only reasonably reproduced at the end. The total mass of relativistic injected particles, given by $\dot{M}_{\rm rel} t_{\rm f}$, amounts to 2.1×10^{-13} $M_{\odot}$ during the injection process. The resultant values listed in Table 2 show that the physical parameters are similar between both plasmons.

3.3. *Comparison between both cases of particle injection*

The values of the physical parameters which describe the expanding plasmon are similar in both cases, and they do not depend significantly on the injection process considered. The main difference arises from the total mass of relativistic electrons necessary to account for the radio emission observed, which for constant injection is a factor 3 above the one considered in case of variable injection. However, this is simply due to the higher value of the magnetic field when variable injection is considered, which compensates the lower value of the mass of relativistic electrons injected.

From Figs. 1 and 3 it can be seen that both types of injection fit the data acceptably well. The double peaked shape of the radio outburst is however more strikingly reproduced in the case of two plasmons with constant injection, while there is a better global fit when using a single plasmon with the time variable injection law of Eq. 4. The lack of observational data between peaks and at the initial time of the outburst hampers our knowledge as to which source injection term should be considered to obtain the best fit to the radio outburst.

The fact that the variable particle injection is not so successful in handling the double peaked structure can be understood

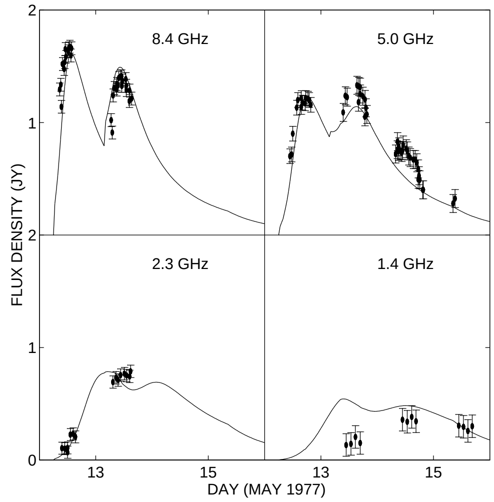

Fig. 3. Data from Haynes et al. (1978) of the 12-15 May 1977 radio outburst compared with the radio light curves computed from our model for the case of constant particle injection rate.

from the dependence on the accretion curve. In the model, it is not an easy matter to obtain the shape of the accretion curve with the sharpness required (unless an extremely high unrealistic eccentricity is assumed) and thus to control the particle injection into a single plasmon in order to reproduce the radio light curve peaks, unlike the two plasmon ejection which is a more powerful mechanism to deal with the peaked structure. A better knowledge of the orbital parameters as well as the stellar wind would allow us to improve the fit.

Finally, we note the possibility of a third peak at 5 GHz, which is not corroborated owing to the lack of simultaneous measurements at 8 GHz. Our model copes with only two peaks. However, a third feature can be accounted for with an additional plasmon ejection in the constant particle injection case, whilst in the variable one a different time dependence of the source term should be considered, although it would not be naturally derived from an accretion curve which only exhibits two maxima.

4. Conclusions

We have extended the application of particle injection models to Cir X-1 in order to reproduce the simultaneous four-frequency radio light curves of the best observed strong radio outburst of this source, as reported by Haynes et al. (1978).

Unlike most previous applications of particle injection models to other X-ray binary systems, the observed data for Cir X-1 are not consistent with the time and spectral evolution expected from a single expanding plasmon with constant injection rate. Therefore, we find it necessary to consider a non-constant injection rate. In particular, the shape of the Haynes et al. (1978) radio outburst can be accounted for by assuming a single plasmon ejection with an injection rate that varies roughly as the accretion rate onto the compact star. Alternatively, this same radio outburst can be interpreted on the basis of two consecutive plasmon ejection events, each of them with nearly the same constant injection rate. From the fits obtained, it is clear that a time variable source term should be included.

Although the particle injection model does not represent a full understanding of the origin of radio outbursts, it does seem to be adequate to provide a first interpretation as well as to constrain the physical parameters to be used in more sophisticated models.

Acknowledgements. We thank J. Martí for valuable discussions and D.L. Jones for helpful comments. JMP acknowledges partial support by DGICYT (PB94-0904). A portion of the research described in this paper was performed while JGS was at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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