

# A search for electron cyclotron maser emission from compact binaries

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## ABSTRACT

Unipolar induction (UI) is a fundamental physical process, which occurs when a conducting body transverses a magnetic field. It has been suggested that UI is operating in RX J0806+15 and RX J1914+24, which are believed to be ultra-compact binaries with orbital periods of 5.4 min and 9.6 min respectively. The UI model predicts that those two sources may be electron cyclotron maser sources at radio wavelengths. Other systems in which UI has been predicted to occur are short period extra-solar terrestrial planets with conducting cores. If UI is present, circularly polarised radio emission is predicted to be emitted. We have searched for this predicted radio emission from short period binaries using the VLA and ATCA. In one epoch we find evidence for a radio source, coincident in position with the optical position of RX J0806+15. Although we cannot completely exclude that this is a chance alignment between the position of RX J0806+15 and an artifact in the data reduction process, the fact that it was detected at a significance level of  $5.8\sigma$  and found to be transient, suggests that it is more likely that RX J0806+15 is a transient radio source. We find an upper limit on the degree of circular polarisation to be  $\sim 50\%$ . The inferred brightness temperature exceeds  $10^{18}$  K, which is too high for any known incoherent process, but is consistent with maser emission and UI being the driving mechanism. We did not detect radio emission from ES Cet, RX J1914+24 or Gliese 876.

**Key words:** Physical data and processes: radiation mechanisms: general – Stars: individual: – ES Cet, RX J1914+14, RX J0806+15, GJ 876 – Stars:binaries : close – Stars: cataclysmic variables - radio: stars – stars: planetary systems

## 1 INTRODUCTION

Unipolar induction (UI) is a fundamental electromagnetic process. For astrophysical systems containing a magnetic and a non-magnetic body orbiting around a common center of gravity, a large e.m.f. is induced across the system by UI when the rotation period of each respective body deviates from one another or from the binary orbital period. If a magnetized plasma is present in the binary environment, an electric current circuit will be set up. The dissipation of the electric currents will heat the magnetic object, which may cause an observational signature. The location where the dissipation occurs depends on the conductivity of the two objects and the nature of the plasma between them; it also depends on the magnetic-field configuration of the system. If the electrical conductivity of the two objects is similar, a dipolar magnetic field will lead to strong heating in regions near the field foot-points of the magnetic object, where the

current density is the highest, as the electric currents are focused by the converging magnetic field lines.

Among all astrophysical UI systems, the best known system may be the Jovian system (Piddington & Drake 1968; Goldreich & Lynden-Bell 1969). The currents flowing between the Galilean moons and Jupiter cause heating on Jupiter, resulting in hot spots and trails on Jupiter’s atmosphere (Connerney et al. 1993; Clarke et al. 1996; 2002). In the Jovian system, the large-scale magnetic field is provided by Jupiter, while volcanism on the moon Io may supply the plasma for the conduction of electric currents (Brown 1994). More recently, two very late-type stars have been found to emit radio emission which varied in its intensity on a period of a few hours, and is polarised and highly variable (Berger et al 2005, Hallinan et al. 2006, 2007). Such properties are consistent with those predicted by the UI model.

It has been suggested that UI processes resembling that

found in the Jovian system can occur in double degenerate binary systems (Wu et al. 2002), and in degenerate star-planet systems (Li, Ferrario & Wickramasinghe 1998; Willes & Wu 2004, 2005). Two candidates for UI double degenerate binary systems are the peculiar X-ray sources RX J0806+15 and RX J1914+24. These objects show light curves which are modulated on periods of 5.4 and 9.5 min respectively - these periods have widely been taken to represent the binary orbital periods (Ramsay et al 2000, Ramsay, Hakala & Cropper 2002, Israel et al 2002). Most of the models which have been put forward to account for these systems have two white dwarfs orbiting around a common center of gravity (eg Cropper et al 2004). Wu et al (2002) proposed that the X-ray emission from both these systems were powered by UI. Since their orbital periods are much shorter than the rotation period of Jupiter's satellites, and since the magnetic field of the magnetic white dwarf is much greater than Jupiter, the currents are much greater and therefore heat the footpoints to X-ray rather than UV temperatures (in the case of Jupiter).

An essence of the UI model for these systems is the large current flows, driven by the induced e.m.f., along magnetic field lines connecting the two objects. For a magnetic object with a dipolar field, the field lines converge to its magnetic polar regions. In such a field configuration, kinetic instabilities such as loss-cone instability can develop easily, leading to electron-cyclotron masers (Wu & Lee 1979; see also Dulk 1985). Moreover, while there is sufficient plasma to provide the charge particles for the current, the plasma density should be low enough to have a low plasma cut-off frequency for the transmission of masers. For double degenerate binaries and stellar planetary systems, some harmonics of these masers are in radio wave-bands (Willes & Wu 2004; Willes, Wu & Kuncic 2005). Moreover, these electron-cyclotron masers are narrowly beamed, have a high brightness temperature ( $\gg 10^8$  K) and are almost 100% circularly polarized. Thus, the detection of strongly circularly polarized emission, (modulated at the orbital period), would provide an unambiguous proof of the presence of UI in these compact systems.

## 2 CANDIDATE UI TARGETS

We sought evidence of UI in various astrophysical systems. These include the systems RX J0806+15 and RX J1914+24 and as a control, we also observed the ultra-compact system ES Cet which has an orbital period of 10.3 min (Warner & Woudt 2002) and shows clear evidence of accretion (Espaillat et al. 2005). While the presence of an accretion flow should suppress UI, it is interesting to search for radio emission around such short period binaries.

Our other target was Gliese 876 (GJ 876) which is a dM4 star at a distance of 4.7 pc with 3 known planets. GJ 876d has an orbital period of 1.94 days and has a mass of  $\sim 7.5_{\oplus}$  (Rivera et al 2005). If the planet GJ 876d has a negligible magnetic field and a metallic core, UI could occur which may drive electron cyclotron maser emission, analogous to the Jovian system. On the other hand if GJ 876d has a substantial surface magnetic field, its field will interact directly with the field of the host star and shield its core from being threaded by the field lines of its dM4

Source	Telescope	$\lambda$	Date	Duration
ES Cet	ATCA	6.1 cm	27 Mar 2005	9.3 hrs
RX J1914+24	VLA	6.2 cm	12 Sept 2005	3 hrs
RX J0806+15	VLA	6.2 cm	26 Sept 2005	3 hrs
RX J0806+15	VLA	6.2 cm	29 Dec 2006	10 hrs
GJ 876	ATCA	12mm	27 Feb 2006	10 hrs
GJ 876	ATCA	12mm	28 Feb 2006	10 hrs
GJ 876	ATCA	12mm	18 Mar 2006	10 hrs
GJ 876	ATCA	12mm	19 Mar 2006	10 hrs

**Table 1.** The log for the radio observations presented here. The Australian Telescope Compact Array is located in Narrabri, Australia, while the Very Large Array is located in New Mexico, USA.

host-star. In this case, field reconnection may lead to particle acceleration, and any radio emission would probably be due to synchrotron radiation and not electron cyclotron maser emission. While the radiation would be expected to be linearly polarized, we would not expect a clear periodicity related to its orbital motion, unless the emission region is localised and eclipsed for a fraction of the orbit.

Willes, Wu & Kuncic (2004) presented calculations for the peak radio flux expected from ultra-compact binaries such as RX J0806+15 and RX J1914+24. For systems with orbital periods in the range 5–10 min, the optimum observing frequency is close to 5 GHz (6cm). For terrestrial planets orbiting around a low-mass magnetic star, the UI model described in Willes & Wu (2005) predicted that the peak frequency is likely to be between 50–500 GHz (0.6–6mm) although this was rather uncertain.

## 3 OBSERVATIONS AND RESULTS

ES Cet and GJ 876 were observed using the Australian Telescope Compact Array (ATCA) in New South Wales, Australia. RX J0806+15 and RX J1914+24 were observed using the Very Large Array (VLA) in New Mexico, USA. We obtained full polarisation information, with the intention of determining the fractional polarisation of any detected source. The observation log is shown in Table 1. In each case, observations took place at two adjacent frequency bands; this provides an increase in sensitivity by a factor of  $\sqrt{2}$  when imaged altogether.

All data were reduced using standard flagging, calibration and imaging routines within the MIRIAD and AIPS packages for the ATCA and VLA observations respectively.

We determined the rms noise level in regions of sky near the known position of each source. We set upper limits on the flux density to be three times the rms noise level. For the one source from which we detected radio emission (RX J0806+15; see Section 3.3), the integrated flux density was obtained by performing a 2-d Gaussian fit to the image.

### 3.1 ATCA observations of ES Cet

The array was in the 6A configuration and observations took place at frequency bands centered on 4800 and 4928 MHz. Conditions were good throughout the observations. PKS 1934–638 and PKS 020–170 were used as flux and phase calibration sources respectively. In order to reduce

any potential contamination of a weak source by artifacts at the centre of the field, the beam was offset by  $\sim 0.5'$  from the desired target. No radio source was found at the position of ES Cet and we determine a  $3\sigma$  upper limit to the flux density of  $72\mu\text{Jy}$ .

### 3.2 VLA observations of RX J1914+24

The array was in the C configuration and the observations took place at frequency bands centered on 4835 and 4885 MHz. Some scattered cloud was present. Flux calibration was performed with respect to 3C286 and 3C48; PKS J1925+2106 was used as the phase reference source. No radio source was found at the position of RX J1914+24 and we determine a  $3\sigma$  upper limit to the flux density of  $42\mu\text{Jy}$ .

### 3.3 VLA observations of RX J0806+15

Observations were obtained for this object at two distinct epochs. In both cases, the array was in the C configuration and the observations took place at frequency bands centered on 4835 and 4885 MHz. Flux calibration was performed with respect to 3C147 for the first epoch and 3C147 plus 3C286 for the second. BWE 0759+1818 and BWE 0748+1239 were used as phase reference sources for the first and second epochs respectively.

During the first epoch we detected an unresolved point-like radio source, coincident, to within the uncertainties, with the optical position of RX J0806+15 (Ramsay, Hakala & Cropper 2002). A Gaussian fit to the image yields an integrated flux density of  $99 \pm 17 \mu\text{Jy}$ , a  $5.8\sigma$  detection with a FWHM of  $4.9 \times 4.2$  arcsec.

The primary calibrator, 3C147, inadvertently used for this observation was not a polarization calibrator. Instead we were obliged to use observations of 3C48, obtained two weeks previously for calibration of RX J1914+24. Whilst not ideal, this allowed us to place some constraints on the circular polarisation. Otherwise, polarization calibration was standard and we obtained a  $3\sigma$  upper limit to the circularly polarized flux of  $52\mu\text{Jy}$ . This is the equivalent of an upper limit of  $\sim 50\%$  fractional polarization.

The second – and longer – observation was made 15 months after the first, and was made to confirm the presence of the radio source detected in the first observation. This second epoch observation resulted in a non-detection, with a  $3\sigma$  upper limit to the flux density of  $36\mu\text{Jy}$ . We plot the resultant images in Figure 1, the left-hand panel showing the first epoch with the apparent source.

We note that the brighter source towards the bottom-left of the field (Figure 1) varies in its flux between the two epochs by  $\sim 70\mu\text{Jy}$ . However, an additional source to the right of the region displayed in Figure 1 remains constant between the two epochs. Therefore we believe that this variability is real and not a calibration artifact.

These results suggest that either the first detection was a chance coincidence with an artifact in the reduction process, or that the radio source is transient. To investigate this further, we split the first observation into eight segments of equal duration and made an image using each individual segment. In only the first,  $\sim 20$  min, segment was the source detected; using this segment a Gaussian fit yielded an integrated flux density of  $128 \pm 39 \mu\text{Jy}$ .

Source	Flux Density
ES Cet	$< 72\mu\text{Jy}$
RX J1914+24	$< 42\mu\text{Jy}$
RX J0806+15 (1)	$99 \pm 17\mu\text{Jy}$
RX J0806+15 (2)	$< 36\mu\text{Jy}$
GJ 876	$< 122\mu\text{Jy}$

**Table 2.** The flux density ( $\pm 1\sigma$  rms noise level) or  $3\sigma$  upper limits for the sources in our survey. The upper limit on the radio emission from GJ 876 is determined from all four datasets combined.

Date of Observation	Phase
27 Feb 2006	0.03–0.24
28 Feb 2006	0.55–0.76
18 Mar 2006	0.53–0.01
19 Mar 2006	0.30–0.51

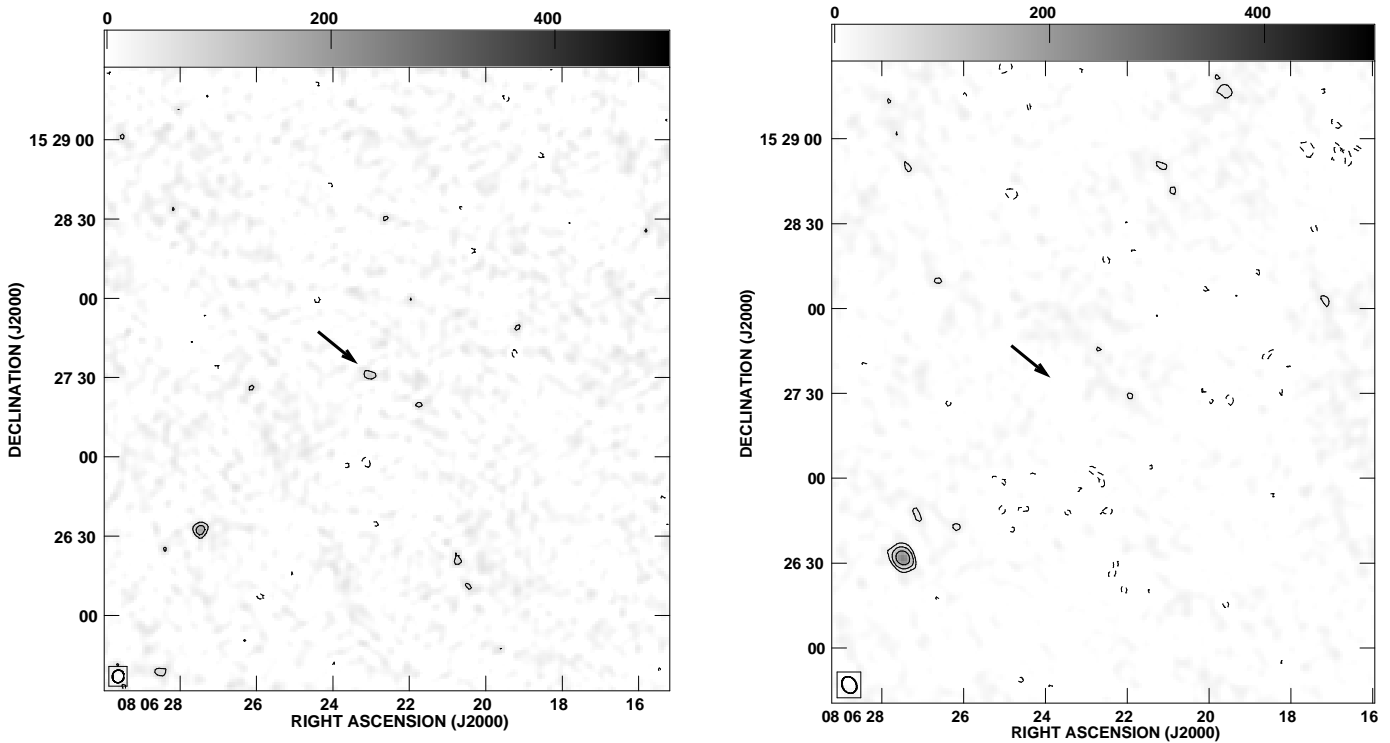
**Table 3.** The orbital phase of GJ 876d at the time of our observations. We used the ephemeris of Rivera (2005) which assumed  $i = 90^\circ$  and  $\phi = 0.0$  was the phase which would result in a transit.

We cannot completely exclude that the radio detection was a chance coincidence between the known source position and an artifact in the data reduction process. However, since the significance is  $5.8\sigma$ , and that the source is variable in the first epoch observation, we believe that it is more likely that we have detected variable radio emission from RX J0806+15. We discuss the implications of this result in Section 4.

### 3.4 ATCA observations of GJ 876

The observations took place at frequency bands centered on 18448 and 19472 MHz over four different epochs. The weather was reasonably favourable for 12-mm observations, although cloud during the afternoons degraded the data quality to some extent. The flux calibration sources were PKS 1934–638 and/or PKS 1921–293; phase referencing took place with respect to QSO B2243-123.

Since the orbital period of GJ 876d is very close to 2 days (1.94 days) it is difficult to obtain ground-based observations which cover the whole orbit from one site. In order to do this we obtained two 10-hour observations within two days and repeated this eighteen days later (see Table 1). We determined the orbital phase of each observation using the ephemeris of Rivera (2005) for GJ 876d (assuming  $i = 90^\circ$ ), which defined  $\phi = 0.0$  as the transit epoch and has uncertainty 0.03 cycles. In Table 3 we show the phase coverage of our observations; we obtained coverage for 90% of the orbital period. However, we did not detect radio emission at any of these epochs, individually or combined into a single image. The  $3\sigma$  upper limit to the flux density in the combined image was  $122\mu\text{Jy}$ .



**Figure 1.** The radio (6 cm) maps of the field of RX J0806+15 made using the VLA in Sept 2005 (left hand panel) and in Dec 2006 (right hand panel). The arrow points to the optical position of RX J0806+15. In the left hand panel the position of the radio source is  $0.3''$  distant from the optical position of RX J0806+15. The beam size is shown in the lower left hand corner of both panels. The rms background noise ( $3\sigma$ ) is  $51\mu\text{Jy}$  for the left hand image and  $36\mu\text{Jy}$  for the right hand image. The contours are -3, 3, 6, 12, 24, 48, 96 times the 1 sigma level.

#### 4 DISCUSSION

Although UI is believed to operate in various astrophysical systems, it has still to be determined if UI is an efficient process in double degenerate binary systems and in magnetised stellar planetary systems. For double degenerate binaries there is an important issue regarding the consequences of UI operation, as it may affect the system's energy budget, and hence the orbital dynamics and evolution (Wu et al. 2002; Dall'Osso, Israel & Stella 2006). Moreover, it will also alter the properties of the gravitational wave emission from these binaries, which are expected to be detected in large number by the proposed *LISA* gravitational observatory (see e.g. Nelemans, Yungelson & Portegies Zwart 2006). It is therefore important to verify and assess the role of UI in compact magnetic binary systems.

The nature of the dominant emission process driving the electromagnetic radiation from RX J0806+15 and RX J1914+24 is not fully known. While the UI model has successfully accounted for many of the observational properties of these two systems (eg Dall'Osso, Israel & Stella 2007), there are a number of properties which will require modification of the generic UI model, which assumes a dipole magnetic field. For instance, it is questionable whether a dipole field can reproduce, in detail, the phase-offset between the X-ray and optical data (Barros et al. 2007). Further, a higher-order magnetic field component needs to be present in order to produce the X-ray and optical light curve profile

(Barros et al. 2005). Therefore, we need more direct, alternative evidence to verify the role of UI in contrast to other processes, such as accretion, in these systems.

In this work we have searched for radio emission from two sources which are believed to be the two most compact binaries yet known. If a magnetic field is present, the electromagnetic interaction between the two stars is expected to be stronger than found in magnetic cataclysmic variables, RS CVn or magnetic Algols, because of the small separation between the stars and the rapid orbital rotation (eg Channugam & Dulk 1982, Retter, Richards & Wu 2005). The detection of radio emission, regardless of its coherence or incoherence, will provide strong evidence of magnetic interaction, and the detection of high brightness circularly polarized emission would confirm the operation of UI on a global scale.

Our observations of ES Cet showed a null detection. The lack of detectable radio emission is not particularly surprising. ES Cet is an ultra-compact binary in which mass transfer occurs via an accretion flow. The presence of an accretion flow also inhibits any large scale current circuit, thus, a global UI process as described in Wu et al. (2002) cannot arise. Although one cannot exclude UI operating in a very small local scale, its effects on the orbital dynamics and on other observational characteristics are not expected to be significant as in other ultra-compact binaries with accretion flows. As loss-cone or other kinetic instabilities cannot develop in accreting systems, ES Cet is not expected to be a

maser source. The presence of high-density material would imply a high plasma-cutoff frequency. For a plasma with electron number density of  $\sim 5 \times 10^{11} \text{ cm}^{-3}$ , the plasma frequency will be well above 5 GHz, thus it will prevent the propagation of 6 cm radio emission, which is the observational band of our ATCA observation.

Our observations do not show evidence of radio emission from RX J1914+24 at a limit of 42  $\mu\text{Jy}$ . One obvious possibility is that UI may not occur in this system. However, the non-detection does not rule UI out. As pointed out in Willes & Wu (2004) the observability of electron-cyclotron masers from a UI double-degenerate compact binary depends on the magnetic moment of the magnetic white dwarf (which determines the frequencies of the cyclotron harmonics), the amount of thermal electrons filling the electric-current flowing magnetic flux tubes, the temperature of these thermal electrons, and the viewing orientation of the binary. Calculations showed that the radio emission is detectable in a restrictive region in the parameter space of UI double-degenerate compact binaries. Thus, even if UI is operating efficiently and electron-cyclotron masers are generated in all systems in an ensemble, some systems will show detectable electron-cyclotron masers in the radio wavebands, while a significant fraction of the systems will show null detection in a radio survey.

We have detected a radio source at a position coincident with the known optical position of RX J0806+15. Although we cannot completely exclude that this is a chance alignment between the known position of RX J0806+15 and an artifact in the data reduction process, the fact that it was detected at a significance level of  $5.8\sigma$  and that the radio source was variable suggests that it is more likely that RX 0806+15 is a transient radio source.

With these caveats in mind, we can determine the brightness temperature  $T_b$  of a source by:

$$\begin{aligned} T_b &\approx \frac{4 \lambda^2 S_\nu}{\pi k_B} \left(\frac{d}{r}\right)^2 \\ &= 3.3 \times 10^{16} \left(\frac{S_\nu}{1 \mu\text{Jy}}\right) \left(\frac{\lambda}{7.8 \text{ cm}}\right)^2 \\ &\quad \times \left(\frac{d}{500 \text{ pc}}\right)^2 \left(\frac{r}{2 \times 10^7 \text{ cm}}\right)^{-2} \text{ K}. \end{aligned}$$

The distance of RX J0806+15 is not well known, with Israel et al (2003) noting that the distance to the edge of the Galaxy is 500 pc, while Barros et al (2007) estimate that its distance is greater than 1.1 kpc implying it is out of the Galactic plane. Assuming a conservative distance of 500 pc and that the size of the emission region is  $\sim 2 \times 10^7 \text{ cm}$  (the linear extension of the foot-point flux-tube for systems with a non-magnetic white dwarf companion with mass  $0.5 M_\odot$ , see Willes & Wu 2004), the observed flux density of  $99 \mu\text{Jy}$  implies  $T_b = 2.1 \times 10^{18} \text{ K}$ . There are some uncertainties about the exact size of the foot-point emission region. Even if we assume that the size of the emission region is  $10^9 \text{ cm}$ , (the radius of a  $0.5 M_\odot$  white dwarf), we still obtain a very high brightness temperature,  $T_b = 8 \times 10^{14} \text{ K}$ . Such a high brightness temperature cannot be explained by non-thermal synchrotron process, which would be limited to  $< 10^{10} \text{ K}$  (Dulk & Marsh 1982). It also cannot be explained by any incoherent radiation processes, as they are limited to

$\sim 10^{12} \text{ K}$  by inverse Compton cooling (Kellerman & Pauliny-Toth 1969).

Therefore, the radio emission must be generated by a coherent radiative process, such as an electron-cyclotron maser as predicted by the unipolar-induction model (Wu et al. 2002). In the maser model described in Willes & Wu (2004), the transient or bursting nature of the source may be explained by variations in the emission-cone beaming direction or by the presence of a small amount of non-thermal electrons whose density fluctuate. To confirm the nature of the radio source we urge further observations of this source at radio wavelengths to determine how often it shows radio emission and to better constrain the upper limit on the circular polarisation.

The fact that we did not detect any evidence for radio emission from GJ 876 does not rule out the operation of UI in this system. Our observations of GJ 876 took place at 12 mm. The calculations of Willes & Wu (2005) suggest that any radio emission due to the UI operation would more likely be observable at shorter wavelengths. Sensitive observations at these wavelengths ( $< 6 \text{ mm}$ ) will be possible using ALMA.

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