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Ultra-compact Double Degenerate Binaries: Gravitational Waves, X-rays and Masers

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Abstract We present a model for unipolar induction in ultra-compact double degenerate binaries consisting of a white-dwarf pair. The power generated by ohmic dissipation of the electric currents driven by unipolar induction is calculated. The orbital dynamics of these ultra-compact systems is investigated, and their gravitational radiation is determined. We also discuss how electron-cyclotron masers develop when unipolar induction operates in ultra-compact double degenerate binaries and related objects, such as the white-dwarf planetary systems.

Key words: stars: binaries: close — stars: white dwarfs — gravitational waves — masers — radio continuum: stars — X-rays: binaries — planetary systems

1 INTRODUCTION

Ultra-compact double-degenerated binaries (UCD) consist of two compact stars, which can be black holes, neutron stars or white dwarfs. In this article, we refer to UCD in a restrictive subclass, in which two white dwarfs revolve around each other with an orbital period $P_{\rm o} \leq 20\,{\rm min}$. These UCD are evolutionary remnants of low-mass binaries, and they are numerous in the Milky Way. The orbital separation of a binary is given by

$$a \;\approx\; 1.1\times 10^{10} \left(\frac{M_1+M_2}{M_\odot}\right)^{1/3} \left(\frac{P_{\rm o}}{600\ {\rm s}}\right)^{2/3}\ {\rm cm}\ , \tag{1}$$

where M_1 and M_2 are the masses of the two stars. UCD with $P_{\rm o} \approx 10$ min or shorter will therefore have an orbital separations smaller than Jupiter's diameter.

Many white-dwarf binaries show magnetism. The best known are the magnetic cataclysmic variable (mCV), in which the white dwarf has a magnetic field B that can reach 100 MG (see Wickramasinghe & Ferrario 2000). This field strength implies a white-dwarf magnetic moment $\mu \sim 10^{34} - 10^{35}$ G cm^3. Given that white-dwarf magnetism is not exclusive to mCV, it is reasonable to expect some UCD to contain a magnetic white dwarf. If the white dwarf in a UCD has a magnetic moment $\mu_1 \sim 10^{34}$ G cm^3, the magnetic field strength will exceed 10 kG at the position of its companion white dwarf. (Here and hereafter, the subscripts "1" and "2" denote the magnetic and the non-magnetic white dwarf respectively, and the subscript "o" denotes the binary orbit.) The compactness of UCD enables strong electro-magnetic interaction between their two white dwarfs. This leads to various exotic observational phenomena, and thus defines the characteristic of these interesting, extreme systems.

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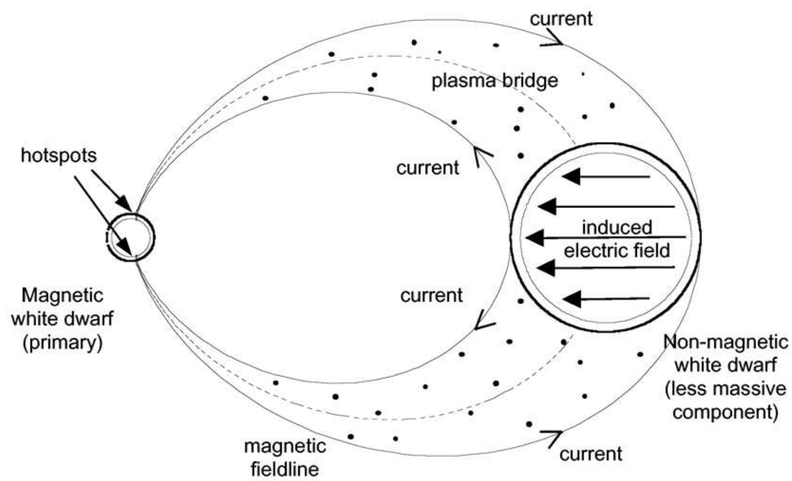

Fig. 1 A schematic illustration of the operation of unipolar induction in a UCD from Wu et al. (2002).

2 UNIPOLAR INDUCTION AND SPIN-ORBIT COUPLING

When a conducting body traverses a magnetic field, an e.m.f. is induced. This e.m.f. can drive an electric current, and when the current dissipates, it extracts energy from the system. The process is known as unipolar induction (UI), and it is fundamental in physics.

White dwarfs have a degenerate core, which is a conducting sphere of electron Fermi gas. The white-dwarf atmosphere comprises atomic matter and has a much smaller electric conductivity than the degenerate core. For a UCD with asynchronous white-dwarf spins and orbital revolution, the operation of UI can induce a large e.m.f. across the non-magnetic white dwarf:

$$\Phi \approx \frac{2\pi}{c}\left(\frac{\mu_1 R_2}{a^2 P_{\rm o}}\right)(1-\alpha)\ , \tag{2}$$

where c is the speed of light, μ is the white-dwarf moment, R is the white-dwarf radius, and α is the degree of asynchronism. With the plasmas in the intervening space providing the charge carriers, a closed current circuit is formed and connects the two stars (Fig. 1). The current flows tend to align with the magnetic field lines to achieve a force-free state. For a dipolar field geometry, the currents therefore converge at the field footpoints near the polar regions of the magnetic white dwarf. The difference in the current densities crossing the atmospheric layers of the two white dwarfs leads to an unequal ohmic dissipation among the white dwarfs. The ratio of their powers is given by

$$\frac{W_1}{W_2}\ \approx\ \beta\left(\frac{\sigma_2}{\sigma_1}\right)\left(\frac{R_2}{\Delta h_2}\right)\left[\frac{G(M_1+M_2)}{R_1^3}\left(\frac{P_{\rm o}}{2\pi}\right)\right]^{1/2}\ , \tag{3}$$

where σ is the white-dwarf atmospheric conductivity, Δh is the atmospheric layer's thickness, and β is a dimensionless parameter of unity order. As $R_2 \gg \Delta h_2$, $W_1 \gg W_2$. The dissipation occurs mainly in two small regions at the surface of the magnetic white dwarf.

If the non-magnetic white dwarf is tidally locked into co-rotation with the orbit but the magnetic white dwarf rotates asynchronously, and there is no mass exchange between the two stars, the orbital dynamics is described by this set of equations:

$$\frac{\dot{\omega}_1}{\omega_1} = \frac{W}{\alpha(1-\alpha)I_1\omega_{\rm o}^2} ; \qquad (4)$$

$$\frac{\dot{\omega}_{\rm o}}{\omega_{\rm o}} = \frac{1}{g(\omega_{\rm o})}\left[\dot{E}_{\rm ext} - \frac{W}{1-\alpha}\right] ; \qquad (5)$$

$$\frac{\dot{\alpha}}{\alpha} = -\frac{1}{g(\omega_{\rm o})}\left[\dot{E}_{\rm ext} - \frac{W}{1-\alpha}\left(1 + \frac{g(\omega_{\rm o})}{\alpha I_1 \omega_{\rm o}^2}\right)\right] ; \qquad (6)$$

$$g(\omega_{\rm o}) = -\frac{1}{3}\left[\left(\frac{q^3}{1+q}\right)G^2 M_1^5 \omega_{\rm o}^2\right]^{1/3}\left[1 - (1+q)\frac{6}{5}\left(\frac{R_2}{a}\right)^2\right] , \qquad (7)$$

where G is the gravitational constant, I is the white-dwarf moment of inertia, W is total electric power dissipation, and $\dot{E}_{\rm ext}$ is other energy loss from the system (e.g. gravitational radiation). How energy is extracted from the orbit and the white-dwarf spins thus governs the evolution and dynamics of the binary. Without UI, the UCD loses orbital energy by emitting gravitational radiation, i.e. $\dot{E}_{\rm ext} = \dot{E}_{\rm gw}$. When UI is in operation, the energy losses are caused by both ohmic dissipation of the currents and by gravitational radiation. (For the details of the UI operation and spin-orbit coupling in UCD, see Wu et al. 2002, also Dall'Osso, Israel & Stella 2007.) Note that the variable $g(\omega_{\rm o}) < 0$ and $\dot{E}_{\rm ext} < 0$. For a system with $(1-\alpha) > 0$, which is the situation when gravitational radiation loss is primary drive of orbital evolution, $-W/(1-\alpha) < 0$. Hence, the orbital angular frequency will increase, as the system evolves (i.e. $\dot{\omega}_{\rm o} > 0$).

3 RADIATIONS FROM ULTRA-COMPACT BINARIES

3.1 X-rays

With only a small deviation from spin-orbit asynchronism, a large e.m.f. can arise in a UCD. Ohmic dissipation of the currents driven by this e.m.f. will generate a power of $\sim 10^{32} - 10^{36}$ erg s^{-1}, escaping from the system as electro-magnetic radiations (Fig. 4). Because of the small sizes of the emission regions, the radiation will be in soft thermal X-rays. It has been suggested that the X-ray sources RX 1914+24 and

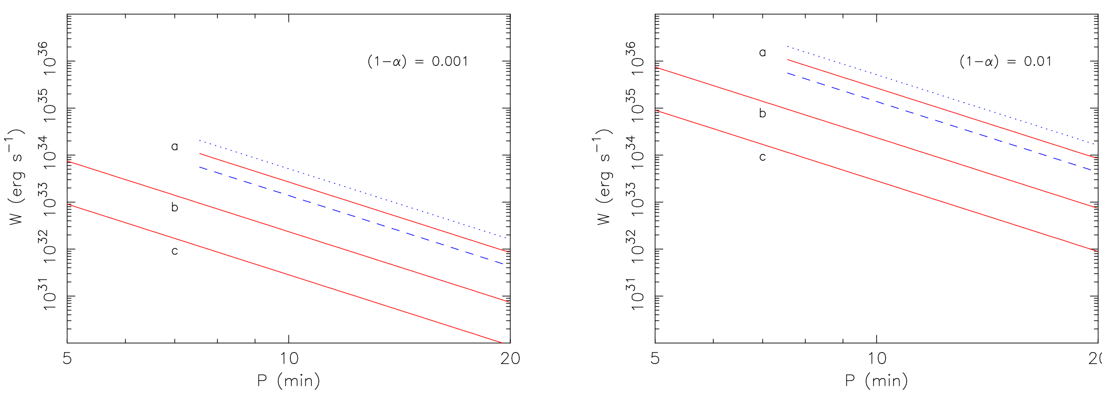

Fig. 2 The total power generated by the current dissipation as a function of the orbital period for spin-orbit asynchromism $(1-\alpha)$ of 1/1000 and 1/100 (top and bottom panels respectively) predicted by the UI UCD model. The solid lines correspond to cases with a 1.0 $M_\odot$ magnetic white dwarf. Lines a, b and c correspond to the cases with a non-magnetic companion white dwarf of 0.1, 0.5 and 1.0 $M_\odot$ respectively. The dotted line corresponds to the case with a 0.7 $M_\odot$ magnetic white dwarf and a 0.1 $M_\odot$ non-magnetic white dwarf; the dashed line, a 1.3 $M_\odot$ magnetic white dwarf and a 0.1 $M_\odot$ non-magnetic white dwarf. The white-dwarf magnetic moments are 10^{32} G cm^{-3} in all cases.

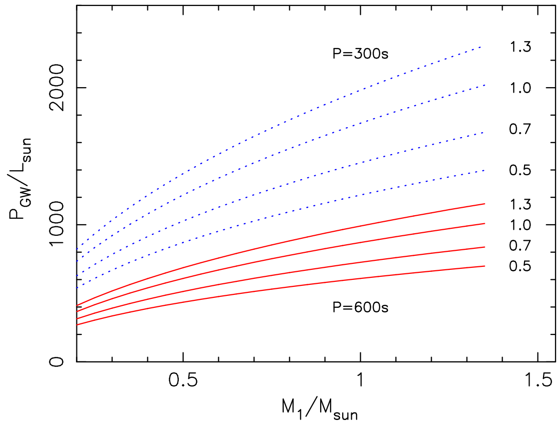

Fig. 3 The power of gravitational waves emitted from UCD as a function of the magnetic white-dwarf mass M_1, for orbital periods of 600 s (solid lines) and 300 s (dotted lines). Each line corresponds to a value of the companion white-dwarf mass, labeled in solar-mass unit. The gravitational radiation power is normalised to the solar bolometric luminosity.

RX J0806+15 are candidate UI UCD (Wu et al. 2002; Ramsay et al. 2002), as they have many peculiar properties difficult to explain in the conventional accreting binary models (Cropper et al. 2004, see also Nelemans 2006). The X-ray luminosities predicted by the UI model are nevertheless in good agreement with those of the two sources, inferred from the *ROSAT* and later X-ray observations (Motch et al. 1996; Cropper et al. 1998; Israel et al. 1999; Ramsay et al. 2005).

3.2 Gravitational Waves

The power of the gravitational waves from a binary system with a circular orbit is

$$\begin{aligned} \dot{E}_{\rm gw} &= -\frac{32}{5}\frac{G^4}{c^5}\frac{M_1^2 M_2^2 (M_1+M_2)}{a^5} \\ &= -\frac{32}{5}\frac{G^{7/3}}{c^5} M_{\rm chirp}^{10/3}\omega_{\rm o}^{10/3} \\ &= -1.2\times 10^{36}\left[\left(\frac{M_{\rm chirp}}{M_\odot}\right)\left(\frac{600\ {\rm s}}{P_{\rm o}}\right)\right]^{10/3} \ {\rm erg\ s^{-1}}\ , \end{aligned} \tag{8}$$

where the chirp mass $M_{\rm chirp} = \bar{M}^{3/5}(M_1+M_2)^{2/5}$, and the reduced mass $\bar{M} = M_1 M_2/(M_1+M_2)$. A UCD with $P_{\rm o} < 600$ s therefore has a gravitational-wave power $\sim 10^{36}$ erg s^{-1}, which greatly exceeds the solar bolometric luminosity. It is now recognised that UCD will be detected in large numbers by the future gravitational-wave observatory *LISA* (see e.g. Cutler, Hiscock & Larson 2003).

As the orbital period evolves, the frequency of the gravitational waves changes accordingly. In the absence of UI, the rate of the change in the gravitational wave frequency can be determined self-consistently, as the orbital evolution is governed by the losses of orbital energy and angular momentum through emission of gravitational waves. In the presence UI, the issue is more complicated. The energy budget is not only determined jointly by gravitational radiation loss and ohmic dissipation of the electric current, but also by energy and angular momentum exchange between the spins of the white dwarfs and the orbit via electromagnetic interaction. Having a proper model for the electromagnetic interaction between the white dwarfs in UCD is therefore crucial for the detection of UCD and for achieving other astronomical objectives that require a proper removal of the contaminations due to the UCD population.

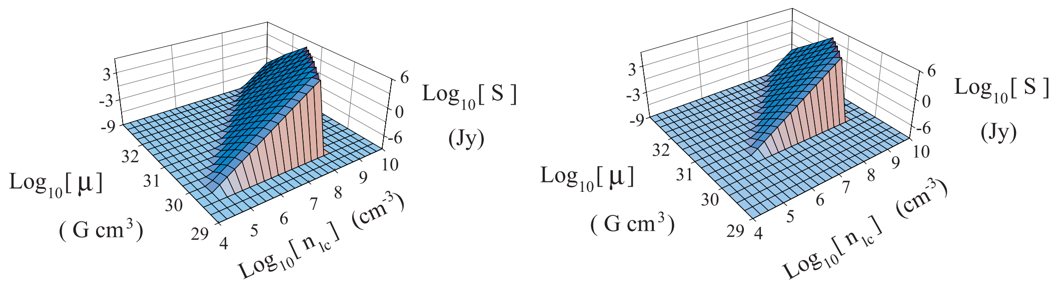

Fig. 4 Predicted angle-averaged flux densities for electron-cyclotron masers, at 5 GHz (left) and 22 GHz (right), from a UI UCD for various loss-cone electron number densities $n_{\rm lc}$ and white-dwarf magnetic moments μ (Willes, Wu & Kuncic 2004). The orbital period is assumed to be 300 s and the distance, 100 pc. The thermal background electron number density is assumed to be $10^8\ {\rm cm}^{-3}$ and have a temperature of $1\ {\rm eV}$.

3.3 Electron-cyclotron Masers – UCD and beyond

The electrons streaming along converging field lines near the surface of the magnetic white dwarf would develop a loss-cone or a shell particle distribution (Wu & Lee 1979). Such an electron distribution is prone to be kinetically unstable, and the presence of a loss-cone or shell instability will provide the free-energy for driving electron-cyclotron masers. Electron-cyclotron masers have the distinctive characteristics of very high brightness temperature and strong circular polarisation (almost 100%). For a UI UCD containing a white dwarf with a magnetic moment $\mu \sim 10^{32}$ G cm^3, the predicted flux density of the electron-cyclotron maser can be as high as 1 Jy, in the $1 - 50$ GHz frequency range, for a distance of 100 pc to the system and an orbital period of 300 s (Willes & Wu 2004; Willes, Wu & Kuncic 2004).

Although it has been argued that UI should operate in UCD as in other astrophysical systems with similar geometrical and magnetic configurations (e.g. Jupiter and its moons, Piddington & Drake 1968; Clarke et al. 2006), how efficient the process is in determining the orbital dynamics and the observation properties of UCD remains uncertain. A firm detection of electron-cylotron masers from UCD will verify the role of UI in these compact systems. Searches for radio emission from UCD have been carried out. There is a recent report that radio flares were detected at the location of the UCD RX J0806+15. The inferred brightness temperature of the emission exceeds 10^{18} K, which is above all known incoherent radiative processes but is consistent with masers (Ramsay et al. 2007). The future detection of circular polarisation would confirm an electron-cyclotron maser origin and hence the efficient operation of UI in UCD.

Note that the maser calculations for UI in UCD can be adapted easily to related UI systems. It was proposed that UI also operates in systems consisting of a white dwarf and a terrestrial planet (Li, Ferrario & Wickarmasinghe 1998). These white-dwarf planetary systems have geometrical configurations and many physical properties similar to those of UI UCD, except that their companions are planets, which are much less massive. However, the maser generation process does not depend sensitively on the mass of the system, so the power of the masers emitted from a UI white-dwarf planetary system and a UI UCD may be comparable (Willes & Wu 2004, 2005). Current instruments could therefore detect the masers from white-dwarf planetary systems. Thus, the masers produced by the UI process provide a new mean to search for terrestrial planets and to investigate the fate of solar-like systems.

4 SUMMARY

We present a UI model for UCD consisting of a magnetic white dwarf and a non-magnetic white dwarf. We determine the spin-orbit coupling and orbital evolution in the presence of UI and gravitational radiation loss. The X-ray and gravitational radiation luminosities of UCD are calculated. We also discuss the generation of electron-cyclotron masers in UCD and predict the flux density of the masers. The application of the maser calculations of UI UCD to UI white-dwarf planetary systems is briefly discussed.

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DISCUSSION

JOHN BECKMAN: Under what circumstances would a system form in which one of the two components was a magnetic white dwarf and the other a non-magnetic white dwarf?

KINWAH WU: It is believed that white-dwarf magnetic fields are fossil fields. If their progenitor stars have different magnetic moments, one of the two components would end up having a strong field. More precisely, two white dwarfs could show magnetism. The magnetic white dwarf and non-magnetic white dwarf are therefore in the context that one has a field significantly stronger than the other to allow unipolar induction as described in the talk to operate efficiently.

JAMES BEALL's Comment: This systems as sources of (possibly) detectable gravitational waves would be an independent test of the field theory, for gravity as well as for electromagnetism. This is a strong argument to gravitational wave detectors and is therefore very interesting.