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Radio Emissions from Terrestrial Planets around White Dwarfs

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Abstract. Terrestrial planets in close orbits around magnetic white dwarf stars can be electron-cyclotron maser sources, by analogy to planetary radio emissions generated from the electrodynamic interaction between Jupiter and the Galilean moons. We present predictions of the radio flux densities from white-dwarf/terrestrial-planet systems and discuss a scenario for the formation of these systems.

1. Introduction

In the unipolar inductor model for the Jupiter-Io electrodynamic interaction (Piddington & Drake 1968; Goldreich & Lynden-Bell 1969), a current circuit is set up along the magnetic field lines connecting Io to Jupiter. The currents are driven by the potential induced across Io, a conducting body, as it traverses the jovian magnetic field. The high energy electrons carrying the current produce an auroral footprint in Jupiter's atmosphere (Clarke et al. 2002). The energetic electrons also produce radio emissions, via an electron cyclotron maser mechanism, which generates a "hollow-cone" radiation pattern (Hewitt et al. 1981). The predicted beaming is consistent with ground and multi-spacecraft observations, which also locate the source near the base of the Io flux tube (Bigg 1964; Dulk 1967; Maeda & Carr 1992; Kaiser et al. 2000).

The electrodynamics in the Jovian system is complicated by the presence of a dense plasma torus surrounding Io's orbit, which inhibits the rapid communication of magnetic stresses (carried by Alfvèn waves) between Io and Jupiter's ionosphere. Io's auroral footprint has two components: a bright point source at the base of the instantaneous Io flux tube, consistent with the predictions of the unipolar inductor model, and a long diffuse tail, which signifies an extended field-aligned current circuit associated with the transfer of momentum from the Io plasma torus to the stagnant plasma in Io's wake (Delamere et al. 2002; Hill & Vasyliunas 2002).

The unipolar inductor model is also valid in systems where Jupiter is replaced by a magnetic white dwarf. Fast Alfvèn speeds associated with high white-dwarf magnetic moments ensure rapid communication of magnetic stresses along the connecting flux tube. The role of the inductor in white dwarf systems can be played by a red dwarf (in AM Her binaries; Chanmugam & Dulk 1983),

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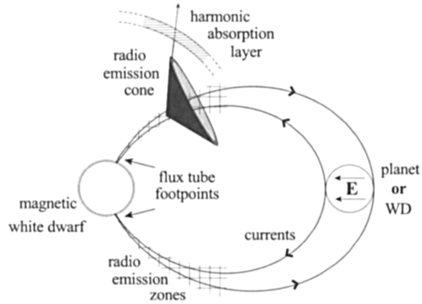

Figure 1. Unipolar inductor model for white-dwarf systems.

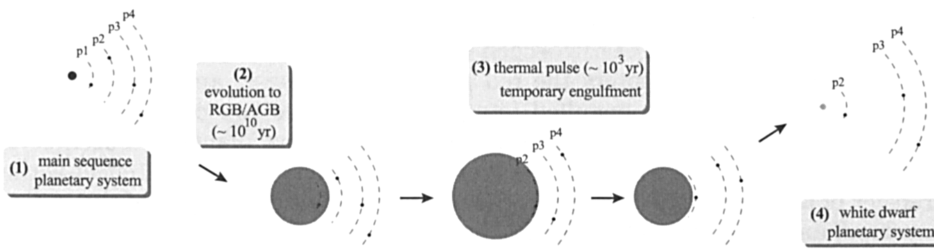

Figure 2. Evolution scenario for white-dwarf/terrestrial-planet systems.

a terrestrial planet core (Li et al. 1998), or an unmagnetized white dwarf (Wu et al. 2002). The induced potential and dissipated power in white-dwarf systems is typically significantly higher than in the Jupiter-Io system.

The most compelling evidence for the applicability of the unipolar inductor model to white-dwarf systems comes from timing measurements of optical and X-ray emissions from two close white-dwarf pairs. A unipolar-inductor model (see Figure 1) can easily explain the peculiar X-ray and optical/IR variations of RX J1914+24 (Wu et al. 2002): the X-rays are powered by resistive heating of the magnetic white-dwarf atmosphere at the base of the flux tube, analogous to the ultraviolet auroral footprints of the Galilean moons in Jupiter's atmosphere. A sub-10-minute orbital period white dwarf pair can produce a footpoint X-ray luminosity well exceeding the solar bolometric luminosity, with only very modest departures from spin/orbit synchronism. The anti-phased optical/infrared emission emanates from the irradiated face of the nonmagnetic white dwarf, which appears as the X-ray source rotates out of view. There is no mass transfer between the white dwarfs, and the orbital period gradually decreases when gravitational radiation from the binary carries away the orbital angular momentum. The unipolar inductor model is consistent with precise timing measurements of X-ray pulses from RX J1914+24 (Strohmayer 2002), and X-ray and optical pulses from RX J0806+15 (Hakala et al. 2003; Strohmayer 2003). In both cases, the orbital period decreases at a rate consistent with gravitational radiation losses, but in contradiction to the predicted period increase by mass transfer models.

We discuss the unipolar inductor model for terrestrial planets in close orbits around magnetic white dwarfs. An evolution scenario for white-dwarf/terrestrial-planet systems and the likelihood that such systems exist are discussed in §2. We present radio flux densities from white dwarf unipolar inductor systems predicted by the unipolar inductor model in §3.

2. Evolution scenario

The first question to consider is: How likely is it that white-dwarf/terrestrial-planet systems exist? Planets first need to survive the major stellar expansion phases as the host star evolves beyond the main sequence (MS). Only planets in an optimum range of orbital distances in the MS system will survive and migrate to close orbits around the emergent white dwarf. We present one possible evolution scenario in Figure 2. At stage 1, four terrestrial planets (p1, p2, p3 and p4) orbit a MS star. As hydrogen burning in the stellar core ceases (after $\sim 10^{10}$ years), the star enters the red giant branch phase, and the innermost planet p1 is permanently engulfed (stage 2). There are two competing effects which determine the orbital evolution of the remaining planets. The first is stellar mass loss, which increases the orbital separation. The second effect is the transfer of angular momentum from the planetary orbit to the spin of the stellar envelope, and this dominates only as the stellar envelope approaches the planet (Rybicki & Denis 2001). This tidal drag acts to decrease the orbital separation. At stage 2, planet p2 may move inwards due to tidal drag, and planets p3 and p4 move outwards. The second major expansion phase occurs at the end of the core helium burning. The asymptotic giant branch phase is characterized by additional short-term thermal pulses, associated with helium shell burning. In each thermal pulse, the stellar radius expands by up to 50% and recontracts, over timescales of $10^2 - 10^3$ years. The predicted number of thermal pulses varies significantly with the parameters used in the stellar-evolution models; e.g., in Sackmann et al.'s (1993) model, the number of thermal pulses decreases from 10 to 5 as the mass-loss parameter (η) increases from 0.4 to 0.6. Thermal pulses provide another mechanism (besides tidal drag) to bring terrestrial planets into closer orbits. At stage 3, planet p2 undergoes temporary engulfment, and it is overtaken by the stellar envelope over the thermal pulse timescale. During temporary engulfment the dominant force is "bow shock" drag, which causes the planet to spiral inwards, by up to 0.3 AU per thermal pulse (Sackmann et al. 1993; Rybicki & Denis 2001). Within an optimum range of orbital separations, a terrestrial planet survives one or more temporary engulfments and is dragged in to a closer orbit around the emergent white dwarf, as illustrated in stage 4.

In this evolution scenario only a small fraction of MS-star/terrestrial-planet systems will evolve into close white-dwarf/terrestrial-planet systems. However this low probability should be balanced by the following considerations: (i) The fraction of MS stars hosting terrestrial planets can be large. For instance, one explanation for the high incidence of moderately elliptical planetary nebulae is that $\sim 50\%$ of planetary nebula progenitors host close, low-mass planets (as low as $\sim 0.01 M_J$; Soker 2001); (ii) The probability increases with the number of terrestrial planets in a MS system; (iii) The number of potential sources in our galaxy is large. Given that $\sim 10\%$ of stars in our galaxy are white dwarfs, and

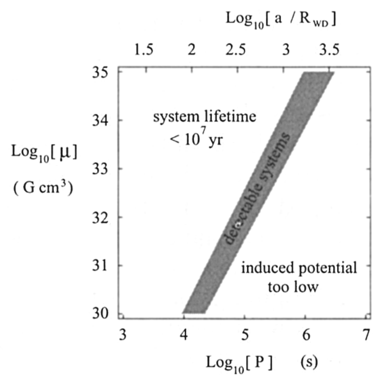

Figure 3. Range of parameter space (white dwarf magnetic moment μ vs. orbital period P and separation a) in which terrestrial planets orbiting white dwarfs are likely to produce detectable radio emissions.

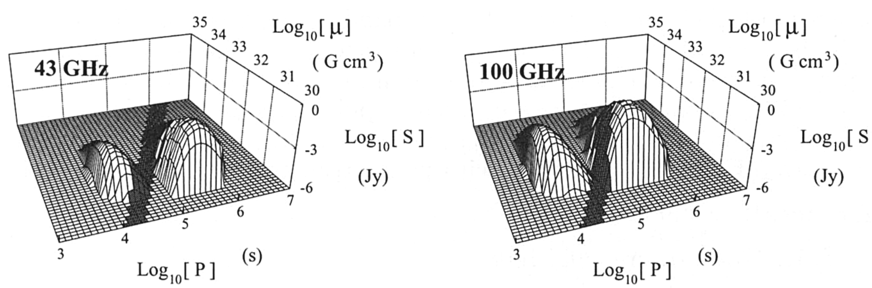

Figure 4. Predicted flux densities at 43 GHz and 100 GHZ (assuming system parameters in text). The grey band denotes the detection band in Figure 3.

that at least 5% of isolated white dwarfs are magnetic, with a larger percentage for white dwarfs in binaries (Wickramasinghe & Ferrario 2000), the number of magnetic white dwarfs in our galaxy exceeds one billion.

3. Predicted radio flux densities

Electron-cyclotron maser emission requires energetic (> keV) electrons as a source of free energy for wave growth. The induced potential across a terrestrial planet scales with white-dwarf magnetic moment as μ, and with orbital period as $P^{-7/3}$ (Willes & Wu 2003). In Figure 3, the region of $\mu - P$ space in which the induced potential exceeds 10^5 V (comparable to the induced potential across Io in the Jupiter-Io system) includes the grey band and the region to its left (assuming $M_{WD} = 0.7 M_{\odot}$, $M_P = 1.2 \times 10^{-6} M_{\odot}$, and $R_P = 3.5 \times 10^8$ cm). An important constraint to the probability of detection for white-dwarf planets is the lifetime of the unipolar-inductor phase and the binary lifetime. The lifetime of the unipolar-inductor phase is limited by the inward drift of the planet due to Lorentz torques. The characteristic lifetime of the white-dwarf planetary

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system scales with binary period as P^5 and with magnetic moment as μ^{-2} (Li et al. 1998). In Figure 3, the region of $\mu - P$ space in which the system lifetime exceeds 10 million years includes the grey band and the region to its right. The grey "detection band" thus represents the region of $\mu - P$ space where a white-dwarf/terrestrial-planet system is both capable of generating radio emissions, and the lifetime of the radio-emitting phase is not prohibitively short.

Willes & Wu (2003) developed a model to predict radio emission flux densities from a white-dwarf/terrestrial-planet system assuming an electron-cyclotron maser mechanism driven by a loss-cone instability in the velocity distribution of accelerated electrons. Figure 4 displays the predicted flux densities at two frequencies, for (i) a white dwarf magnetosphere with constant density $n_{\rm th} = 10^7\,{\rm cm}^{-3}$, and thermal temperature $k_{\rm B}T_{\rm th} = 1$ eV; (ii) electrons accelerated to 1 keV energies in the unipolar inductor current circuit; and (iii) 1% of current electrons contributing to the loss-cone instability, with an angular loss-cone width $\Delta\alpha = 0.01$.

Points to note concerning Figure 4 are that: (i) > mJy flux densities are predicted over a relatively broad range of $\mu - P$ space. Note that radio detections are most likely in the grey detection band. Comparison of the two panels reveals that the predicted flux densities are strongly frequency dependent; (ii) The predicted radio emissions are 100% circularly polarized, with the two humps corresponding to opposite senses of circular polarization; and (iii) By analogy to the Jupiter-Io radio emissions, the predicted radio emission will have short duty cycles (of typically a few %), with pulses recurring at the orbital period.

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