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Development of a Parallel Fully Relativistic 3-Dimensional Particle-in-Cell Model of Electron Cyclotron Maser Emission from Brown Dwarfs

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Radio and X-ray observations of brown dwarfs in recent years have unexpectedly confirmed the presence of coronal magnetic activity in these substellar objects. Furthermore, the radio emission from a number of these objects substantially violates the observationally established Güdel-Benz relations coupling the X-ray and radio luminosities of coronally active stars. It is proposed that an electron cyclotron maser (ECM) may be responsible for the coherent, highly polarized, flaring component of this anomalous radio activity. It is also proposed that the plasma instability required to generate this emission is not the conventional loss-cone distribution. Instead a shell distribution analagous to that responsible for Auroral Kilometric Radiation (AKR) will be investigated as a possible source. It is the intention of the authors to develop a parallel fully relativistic 3-dimensional TRISTAN based particle-in-cell code to investigate the conditions where an ECM can operate in the coronae of brown dwarfs. These simulations will be correlated with ongoing Very Large Array (VLA) observations of radio active brown dwarfs in an attempt to fully establish the exact nature of this peculiar radio emission.

1. Introduction

The means by which a dwarf star such as our Sun develops and maintains a low density, high temperature, highly ionized layer known as a corona, in its outermost atmosphere remains uncertain. What is clear however, is that the presence of a corona is intimately related to the existence of large scale magnetic fields that permeate the atmosphere of the star. The more prevalent theories for coronal heating include heating by acoustic magnetohydrodynamic waves generated by turbulent convection and heating by the impulsive release of magnetic energy in flares, microflares and flare-like events. In the latter case the flares are produced by magnetic reconnection in coronal loops. The resultant release of magnetic energy accelerates ambient electrons to very high energies forming the power-law distribution associated with incoherent processes such as synchrotron and gyrosynchrotron emission. These electrons in turn heat the underlying chromospheric material, driving a discharge of hot plasma from the chromosphere into the corona (chromospheric evaporation) with the interaction of the electrons with the outflowing plasma producing bremsstrahlung X-rays. This causal connection between the particle acceleration, which is a source of radio emission, and plasma heating, which results in X-ray emission is in essence the Neupert effect.

Neither of these processes (or other processes proposed in the literature) can be rejected out of hand and may in fact all contribute in one way or another to coronal heating. The key to understanding which processes predominate is the coronal and chromospheric emission extending from the radio to the X-ray regime. Correlation of observations at these various wavelengths has established empirical relationships between the X-ray and radio luminosities, both quiescent (slowly varying) and flaring (higher energy, rapid variation), of main sequence dwarf stars (Güdel & Benz 1993) . These relationships, referred to as the Güdel-Benz relations, hold over several orders of magnitude over much of the low-mass stellar main sequence and point to a process of coronal heating that involves particle acceleration (such as the magnetic connection model described above) that is ubiquitous for this spectral range. However, the Güdel-Benz relation was only established observationally down to spectral type M7 The question whether magnetic activity, X-ray emission and the Güdel-Benz relation holds in the region of the coolest M dwarfs ($>$ M7) and into the substellar regime of brown dwarfs immediately arises.

2. Magnetic activity on brown dwarfs

Below the stellar mass limit of $\sim 0.075 M_{\odot}$, the realm of brown dwarfs have attracted immense attention since the first conclusive identification of their existence in 1995. Below this mass limit the cores of these objects are no longer able to reach the temperature required for sustained hydrogen fusion. However those with mass $> 0.013 M\odot$ can burn deuterium during a short episode lasting $\approx 10^7$ yr distinguishing them from lower mass objects.

A reduction in magnetic activity is expected as we move from very low mass stars to the substellar regime of brown dwarfs. The photospheres of evolved brown dwarfs are dominated by molecular hydrogen, with a very low ionization degree and high electrical resistivity. Therefore currents should not flow into the almost neutral photosphere resulting in magnetic fields lines that are largely decoupled from the upper atmosphere. Furthermore, brown dwarfs are fully convective objects and the classical $\alpha - \omega$ dynamo can thus no longer operate due to the absence of the radiative core although a turbulent or (α^2) dynamo may become relevant.

Observations of brown dwarfs at X-ray and H-α wavelengths (representing coronal and chromospheric activity respectively) do indeed reveal a sharp drop in quiescent magnetic activity but the occurrence of flaring emission does not appear to drop off as rapidly. This high-energy emission is strong evidence that magnetic fields are indeed present despite the theoretical expectations outlined above. Even with this unusually high flaring X-ray luminosity taken into account, the corresponding radio emission predicted from the Güdel-Benz relations is exceedingly weak. Using the VLA (Berger et al. 2001) observed the location of the first X-ray detected evolved brown dwarf LP 944-20. According to the Güdel-Benz relations, for the X-ray flare peak luminosity $L_X \approx 1.2 \times 10^{26} ergs^{-1}$ the predicted flare radio flux density $F_{\nu R} \approx 0.1 \mu Jy$ with a quiescent value less than $0.01 \mu Jy$; no radio activity should be observed. In stark contrast, it was discovered to be a copious source of persistent and flaring radio activity with flux density values of $80 \mu Jy$ and $2000 \mu Jy$ respectively. These figures are over four orders of magnitude higher than expected and represent a massive violation of the Güdel-Benz relations. Since that initial discovery there have been more than a dozen further detections of radio emitting brown dwarfs, including one other previously confirmed X-ray source.

Analysis of the quiescent emission from these objects yield brightness temperatures of $\sim 10^8 - 10^9 K$, electron densities of $\sim 10^{12} cm^{-3}$ in weak (10-100 G) magnetic fields suggesting gyrosynchrotron emission from mildly relativistic electrons. On the other hand, the higher brightness temperature ($\sim 10^{12} K$), short period (~ 2 minutes), high linear polarization, and apparently narrow spectral bandwidth of the flare emission from one brown dwarf DENIS 1048-3956 (Burgasser & Putman *in press*) points to a coherent emission process with the electron cyclotron maser favored over plasma radiation at the wavelengths in question (~ 3.6 cm).

3. The electron cyclotron maser as a source of radio emission

The ECM is a plasma instability caused by the resonance between electromagnetic waves at frequencies near the electron cyclotron frequency (and perhaps its low harmonics) and plasma electrons in the presence of an externally generated magnetic field. However, the resonance only leads to the instability if the velocity distribution of the electrons has a particular kind of anisotropy. It has been postulated as a source for a number of radio emissions including planetary radiation from all of the magnetized outer planets, solar microwave spikes associated with impulsive flares, solar type V radio emissions, radio emissions mechanism from binary systems and narrowband emissions from dwarf M flare stars (Ergun et al. 2000 & references therein). An important milestone in the understanding of ECM was the description by (Wu & Lee 1979) of auroral kilometric radiation (AKR), in which they used the semi-relativistic approximation demonstrating that masers could operate under much milder, relatively common astrophysical conditions than previously thought - e.g. in a loss cone distribution, later developed into the electron-cyclotron maser instability (Melrose and Dulk 1982). However, further investigation in the following years revealed that direct observation of the X-mode radiation generated from a loss-cone maser in a stellar source seemed unlikely due to gyresonance absorption of the radiation at harmonic layers of the local gyromagnetic frequency.

More recently, electromagnetic field and charged particle observations within the AKR source region (Ergun et al. 2000) confirmed that AKR was indeed due to the weakly relativistic electron cyclotron maser instablity, but not due to a loss-cone instability as had been previously thought. Instead evidence pointed to generation of the wave emissions by a “shell” instability that results from electron acceleration by a parallel electric field in a dipole magnetic field, a theory initially proposed by (Pritchett 1984). As electron beams resulting from the electric fields move into stronger magnetic field regions they form a crescent or “horseshoe” distribution as a result of the first adiabatic invariant . These particular electron distributions have been shown by (Bingham & Cairns 2000) to be unstable to the generation of R-X mode radio emission. In the case of stellar maser emission the beam can arise as a result of of flare activity in the equatorial region of the star where the rapidly expanding flare can interact with the dipole field structure creating a shock propagating outwards. The resultant radiation, guided by a density cavity that is created by the parallel electric field, can be very efficiently converted to the R mode which experiences substantially lower absorption at higher harmonics (Ergun et al. 2000).

The shell instability seems the more likely source for the maser emission from brown dwarfs for a number of reasons. It is now confirmed as the source of terrestrial radiation, is a more powerful source, and is directly associated with particle acceleration. Also, there are many characteristics that can be attributed to the shell maser that are outside the range of those associated with the loss cone maser. These include continuous emissions with high brightness temperature $> 10^{14}$ K, broadband emissions, and emissions from high above a stellar surface (Ergun et al. 2000). It is the intention of the authors to investigate the possibility of maser emission generated by a shell instability through TRISTAN based particle-in-cell simulations, initially of isotropic beams moving into stronger magnetic field, and eventually possible shell instabilities consistent with source conditions in the coronae of radio-active brown dwarfs. These simulations will be correlated with recent Very Large Array (VLA) observations of these objects in an attempt to fully establish the exact nature of this peculiar radio emission.

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