Giant "Pulsar" Studies with the Compact Array

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Abstract

I present recent results from work at the ATCA on stellar pulsars. Five objects, including the Ap star CU Vir and a set of ultracool dwarfs have been found to emit periodic radio pulses that are up to 100% circularly polarised. I followed up a selection of these with the ATCA, more recently with the Compact Array Broadband Backend. Initial results show intriguing wide-band properties. I hope to discover more such objects through a volume-limited survey of southern ultracool dwarfs. This field offers a unique and highly important window onto stable structures and physical processes in the magnetospheres of a variety of stars.

Introduction

Studying stars as a population of radio sources is hard. To begin with, the menagerie of stellar radio emitters is large and vociferous: objects from cool dwarfs to giants to pre-main sequence T Tauri stars to the hotter Ap and Bp stars, to Wolf-Rayet stars all exhibit fascinating radio properties (Güdel 2002). Add to this the generally small samples of sources of any one particular type, and exceptional variability on many timescales, and one is left with a field that inspired Güdel (2002) to quote Albert Einstein:

"…all our science, measured against reality, is primitive and childlike: and yet it is the most precious thing we have."

This article shall be restricted to stellar radio transients. The project was begun by a group of pulsar astronomers venturing into greener pastures: hence, it may be assumed that these transients are periodic, or *stellar pulsars*. Isolated radio flares of few-minute durations, non-thermal brightness temperatures and almost total circular polarisation have been observed from stars of almost all types with spectral classes F or cooler. Non-thermal radio emission from stars is associated with energetic plasmas propagating through magnetic fields. The plasmas are accelerated as parts of stellar winds, or through magnetic field reconfiguration events. The physics of stellar flares is mainly understood through radio observations of the Sun. Indeed, various types of solar and stellar flares were shown by Güdel & Benz (1993) to all have the same ratio of X-ray to radio luminosities. Flares from stars besides our Sun, however, are many orders of magnitude more spectacular than those from the Sun: a recent X-ray flare from the nearby M-star EV Lac briefly increased its total energy output by a factor of ~3 (Osten et al. 2010). We could not live very long close to such a star!

Stellar pulsars offer a new dimension to the study of stellar magnetic environments: stability. Without modulation of the radio signal from a star, and without extremely high-resolution radio imaging, nothing can be said about the structure of the magnetic environments, or *magnetospheres*, of stars. Optical studies of periodic variability, while excellent for studying stellar surfaces, are only weakly affected by the surrounding magnetospheres. Periodic radio emission from stars, originating in the magnetospheres themselves, offer a unique insight into stable structures and physical processes in stellar magnetospheres. This is hugely important, because the magnetic fields of many stars are little understood. Magnetic fields are crucial to stellar evolution, from the highly magnetised Ap/Bp stars that
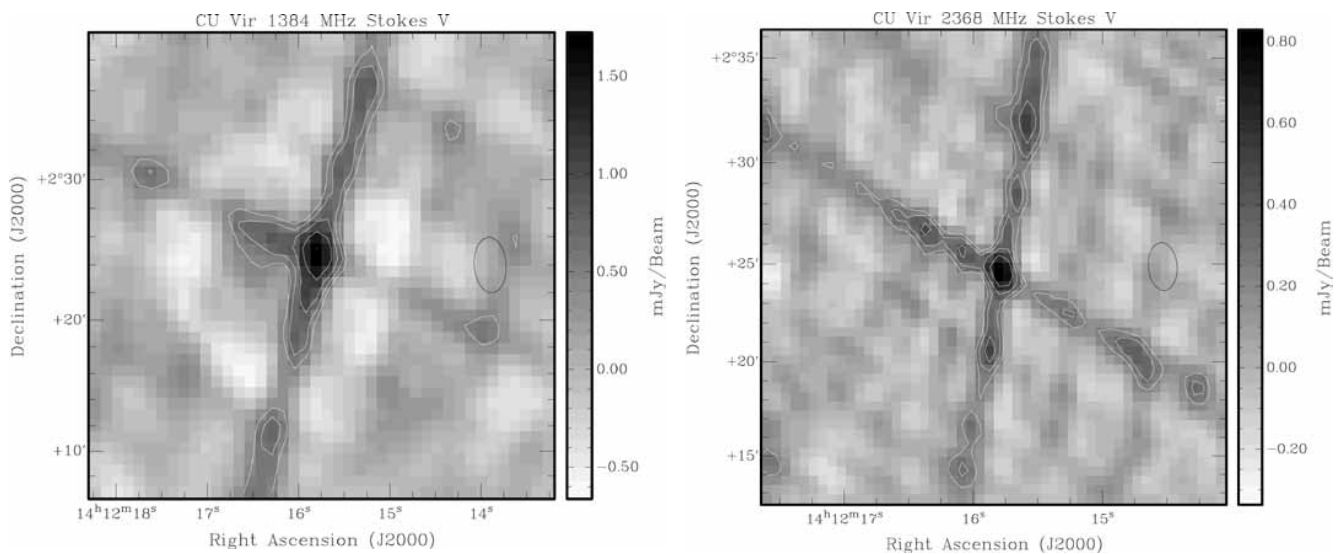
Figure 1: Stokes V ATCA images of CU Vir at 1384 MHz (*left*) and 2638 MHz (*right*). The peak flux densities in the images are 1.72 mJy/beam and 0.83 mJy/beam. Contours begin at a fourth of the peak fluxes and increase in factors of 1.4. The synthesised beam FWHM are displayed to the right of the images, and the greyscale bars beside the images give the flux density scale in mJy/beam. Image credit: Vikram Ravi

evolve into neutron stars, to very low-mass stars and brown dwarfs at the planet/star transition that exhibit significantly different magnetic properties to higher mass stars.

Only a few stellar pulsars have been discovered to date. Stellar pulsars are different from stars with always present, but modulated, radio emission properties in that the pulsed component is not present for the entirety of a rotation period. Known stellar pulsars include the main-sequence star CU Vir (Trigilio et al. 2000), and four ultracool dwarf stars (Hallinan et al. 2007, 2008; Berger et al. 2010) just massive enough to sustain nuclear fusion. It is striking that in all cases, the pulses are highly circularly polarised, with fractional Stokes V percentages of between 60% and 100%. While this is not uncommon in solar and stellar (and even planetary!) radio astronomy, this might sound absurd to an astronomer used

to measuring circular polarisation fractions of a few tenths of a percent from active galactic nuclei.

Here, I shall outline our investigations of CU Vir and a sample of ultracool dwarfs with the Australia Telescope Compact Array (ATCA) undertaken since 2008. In the process, I hope to convince the reader of the fascination of studying both big stars that chug and chug, and little stars that could.

CU Vir: I Can Be a Pulsar Too!

CU Vir is a magnetic chemically peculiar (MCP), CP2 α^2 CVn A0 (and sometimes B9) star (Deutsch 1952). What this means in practical terms is that it is a hot, highly magnetised star with unusual surface spots of silicon and helium. Cu Vir is the fastest rotating star of its type, with a rotation period of ~12.5 hours (Pyper et al. 1998). This implies a surface velocity

more than three times that of a pulsar! The magnetic field of CU Vir approximates an offset dipole with a polar field strength of 3000 G (Trigilio et al. 2000).

Twin peaks of completely circularly polarised radio emission per rotation period were discovered by Trigilio et al. (2000) at an observing frequency of 1425 MHz with the Very Large Array. This was later confirmed by Trigilio et al. (2008) using the ATCA. The dual L and S band observing mode of the ATCA also enabled the discovery of pulsed emission at 2496 MHz: however, only a single peak was seen at this frequency. I observed CU Vir in October 2008 with the ATCA simultaneously at 1384 MHz and 2638 MHz (Ravi et al. 2010), as part of a project to search for transient emission from isolated white dwarfs (none was found). The resulting images at both frequencies in circular polarised intensity (Stokes V amplitude) are shown in Figure 1.

And don't they look weird! While similar features in synthesis images sometimes represent calibration errors, the clear association with the source is a telltale sign of them being celestial in origin. They are in fact artefacts of the emission peaks. The instantaneous beam of a linear interferometer like the ATCA in its extended six-kilometre configurations is a series of strips tapered by the primary beam response. If the source only exists for a short part of a track, only a few instantaneous beams are added in the image, creating the "fan beams" evident in Figure 1.

Two sets of fan beams at similar position angles are evident at both observing frequencies. These represent two peaks of 100% right-circularly polarised emission at both frequencies. An analysis of the arrival time of the peaks I observed in relation to those seen previously confirmed an intriguing result reported by Trigilio et al. (2008). The radio observations of CU Vir indicate that its period decreased abruptly in 1998 by 2.2 seconds with respect to previous the optical rotation ephemeris. A smaller period change occurred in 1985 (Pyper et al. 1998). The cause of these period changes is as yet unknown, but could be linked to violent mass-loss from the magnetosphere (Trigilio et al. 2008).

I averaged the ATCA observations of Trigilio et al. (2008) with mine to produce the average pulse profiles shown in Figure 2. Strikingly, the higher frequency peaks appear at slightly offset pulse phases to the lower frequency peaks. This effect, first pointed out by Trigilio et al. (2008), offers a key to understanding the structure of the magnetosphere.

Every good model needs some nice, believable assumptions, followed by some not-so-believable ones that are being tested. First, it is highly likely that the emission mechanism is an electron cyclotron maser (ECM). ECM emission has been directly studied in the Earth's atmosphere in the form of the Auroral Kilometric Radiation, and in the laboratory (Melrose & Dulk 1982). It is a coherent mechanism, which produces circularly polarised emission in a cone nearly perpendicular to magnetic field lines. ECM emission occurs in an extremely narrow band about the local cyclotron frequency, which scales linearly with the magnetic field strength. ECM emission is hence extremely useful as a precise magnetic field strength indicator, and as a tracer of regions of constant magnetic field strength.

I showed that simulated pulse profiles generated using a model with a simple dipolar magnetic field could not reproduce the observed pulses. Trigilio et al. (2011) suggested that the pulses are refracted in a dense region of the magnetosphere close to the star. In contrast, Lo et al. (2011, submitted to MNRAS) suggest that the emission is instead ducted through cavities along the field lines to higher emission heights, and then radiated. Further wide-band observations are required to distinguish between these models. Such observations are being carried out using the new Compact Array Broadband Backend (CABB) at the ATCA.

Not Just Cool, But Ultracool Dwarfs

I have completed a survey of all 15 known ultracool dwarfs within 10 pc in the Southern hemisphere with CABB at the ATCA. Our sample was chosen from stars that straddle the hydrogen-burning star and brown dwarf divide, with spectral types ranging from M7 to L. Since 2001, 14 ultracool dwarfs have been detected in flaring, pulsing or quiescently emitting states (Berger et al. 2010). Notably, all violate the radio/X-ray relation mentioned above. Furthermore, changes in the type of emission on timescales of years, and surface magnetic field strengths of many-kiloGauss, both make for one confusing bunch of stars.
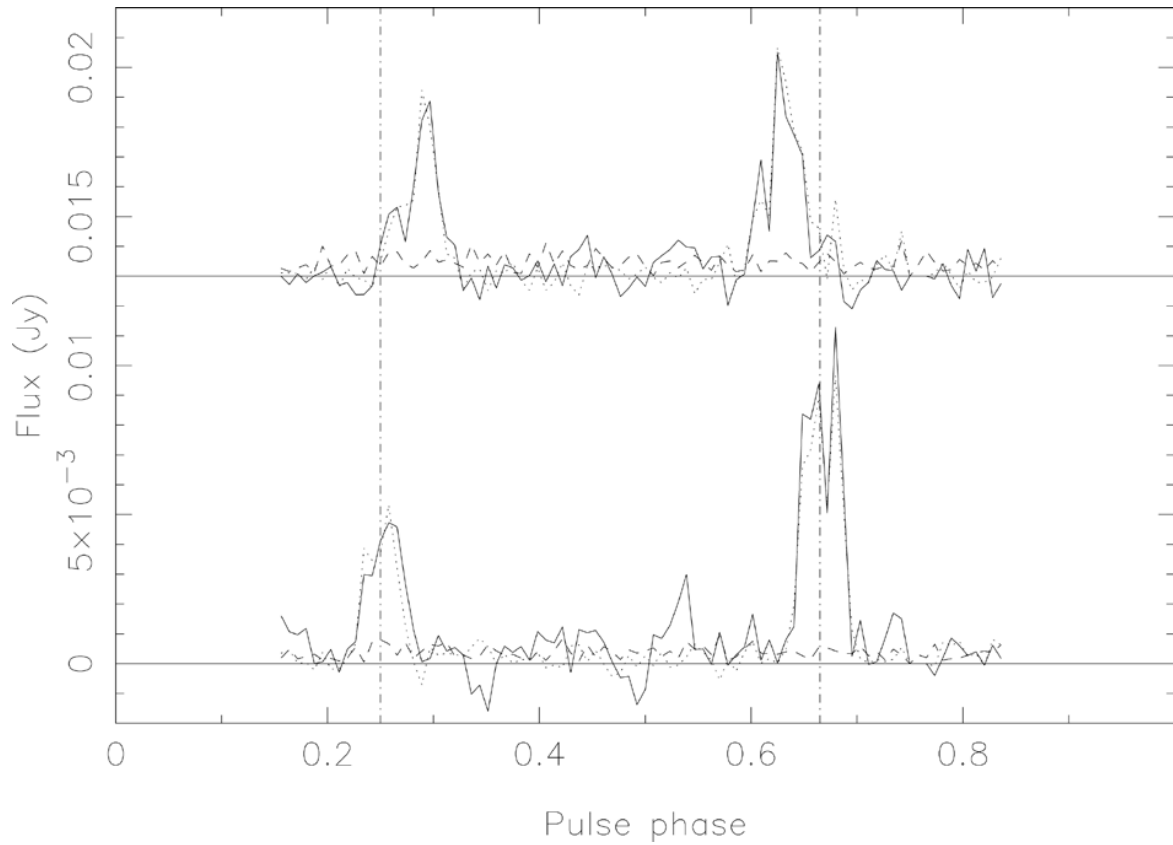
Figure 2: Average pulse profiles in the S-band (*top*, offset by 13mJy) and L-band (*bottom*) obtained by aligning and averaging the pulses observed by Trigilio et al. (2008) and us. We plot Stokes I (solid curves), Stokes V (dotted) and linear polarised intensity (dashed). The vertical dot-dashed lines represent the centres of the pulses at 20 cm. Image credit: Vikram Ravi

As a precursor to the survey, I observed the ultracool dwarf DENIS-P J104814.9− 395604 (DENIS 1048) with the ATCA in August 2009 at 5500 MHz, 9000 MHz, 18000 MHz and 24000 MHz (Ravi et al. 2011).

Burgasser & Putman (2005) had previously detected 100% circularly polarised flares each at 4800 MHz and 8640 MHz and quiescent emission from DENIS 1048. The flare was attributed to an ECM mechanism, and our observations were intended to study the wide-band characteristics of any emission observed.

To my mild despair, I detected no flares. I did however find a strong, stable source with a strikingly

regular power-law spectrum (Figure 3). Circular polarisation percentages of up to 40% were also detected. The results were consistent with an incoherent emission mechanism, as opposed to partially-depolarised ECM emission as was previously suggested for ultracool dwarfs (Hallinan et al. 2008). In an ECM model, the lack of modulation, combined with the detection at 18000 MHz would suggest that a region of magnetic field strength of ~6400 G would have to cover most of the stellar surface. This is inconsistent with optical measurements of the surface field strength (Berger et al. 2010). I modelled the emission as originating from the co-rotation radius in the magnetosphere, and
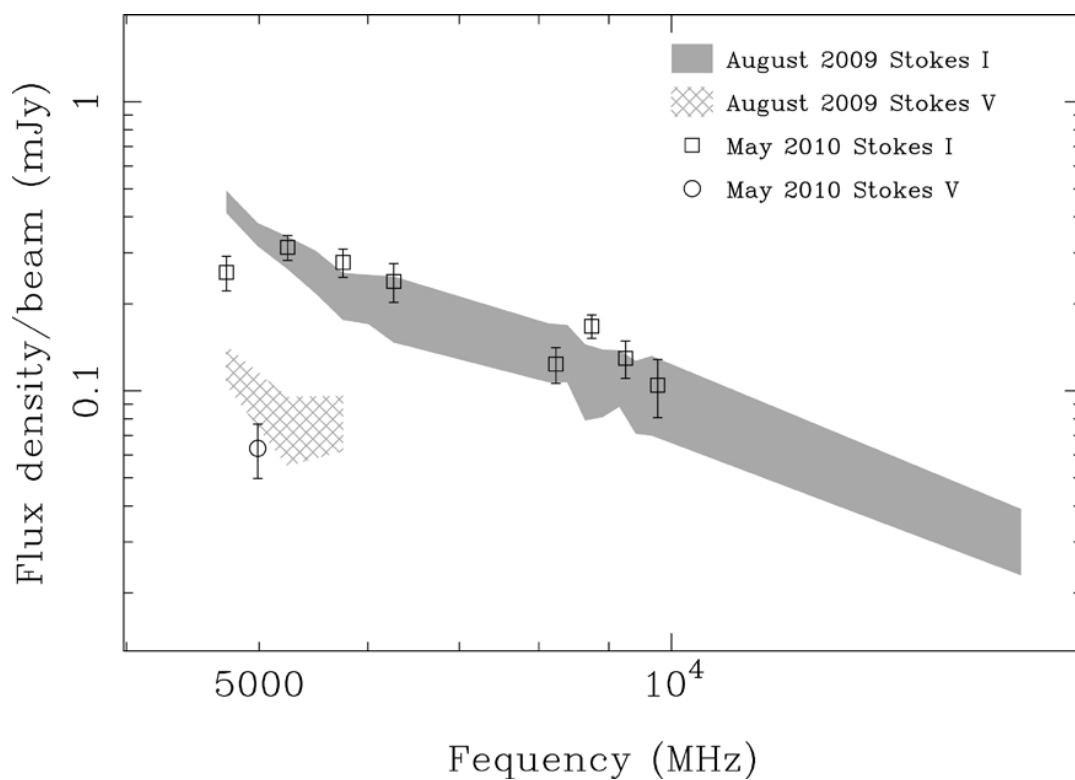

Figure 3: The wideband spectrum of DENIS 1048 obtained on two epochs with ATCA-CABB. The 1σ error range August 2009 spectrum is shown as shaded (total intensity) and cross-hatched (circular polarisation) regions. The squares and circles represent the May 2010 spectrum in total intensity and circular polarisation respectively. Image credit: Vikram Ravi

limited this, the relativistic electron density and the magnetic field strength in the emission region.

Preliminary results from the ultracool dwarf survey are promising. An analysis of data on DENIS 1048 obtained in May 2010 show that the radio emission properties appear much the same (see Figure 3), besides a possible dip in the emission at the lowest frequency. Broadband images achieve sensitivities of 8 μJy or better. The goals of this survey are to attempt to increase our sample of ultracool dwarf radio sources, particular pulsing ones. The large CABB bandwidths will enable fantastic dynamic spectra of any time-variant emission to be made. I will also stack all non-detections to understand whether any residual radio emission is present. Together, these results will begin to characterise the various states of this enthralling class of sources.

Concluding Remarks

Can we refer to stars that show periodic radio emission with fractional duty cycles as pulsars? A quick search of the ATNF Pulsar Catalogue (Manchester et al. 2005) will not reveal either CU Vir or any of the periodically emitting dwarfs. A pulsar, however, is nothing but a radio source — neutron star or not — that emits radio pulses which fit

a rotation model. By this definition, CU Vir and the ultracool dwarfs are certainly pulsars. Neutron star pulsars, though, are more than just lighthouses. They have characteristic pulse profiles that are stable on long timescales, which are used to study the pulse emission region and in pulsar timing. The dynamics of neutron star pulsar magnetospheres are primarily influenced by the rotation, and the emission is coherent and beamed. The stellar pulsars share these properties. To stretch the analogy, CU Vir appears to undergo the analogue of pulsar glitches. Looking to the future, then: if stellar pulsars can reveal anywhere near as much about their hosts as neutron star pulsars, the field looks set to be quite exciting indeed. Two Nobel prizes? Who knows!

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