Exploring Cosmic-ray acceleration in the Galactic realm

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This thesis is dedicated to my Family, and to Phil Teare, who inspired us all with his humor and his intelligence.

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Abstract

Despite many years of research dedicated to elucidating the conditions in which cosmic rays (CRs) are accelerated, there is still great uncertainty about exactly how such particles are accelerated up to energies of 1 TeV (1 TeV= 10^{12} eV) and well beyond. Additionally, there is also great uncertainty about the structure and amplitude of the Galactic magnetic field which necessarily has a great impact upon the movement and interaction of CRs in the Galaxy. This thesis deals with a number of ways in which Gigahertz (GHz) frequency radio continuum observations can be used with GeV–TeV γ-ray observations to explore (i) the CR spectrum and (ii) the magnetic field amplitude in the Galaxy. An accurate knowledge of the CR spectrum and amplitude of the magnetic field has important consequences for a wide range of phenomena, such as particle acceleration and even star formation within the Galaxy.

We present a simple static, single-zone model of secondary electron and positron production from CR protons and heavier nuclei interacting with ambient matter. We then apply this model, assuming a local CR spectrum, to predict the synchrotron emission from two cold, dense, massive molecular cores which are relatively nearby using a prescription for the magnetic field which scales as the (approximate) square-root of the hydrogen number density. Radio continuum observations with the Australia Telescope Compact Array (ATCA) are then used to search for this emission and, due to the lack of detection, upper limits to the magnetic fields within these cores are obtained. We find that these limits are not inconsistent with the prescription used in the theoretical modeling.

We also present observations of a giant molecular cloud located in the Galactic centre (GC) region, Sagittarius B2 (Sgr B2), chosen because of the expectation of a higher CR flux (than that observed at the top of the earth's atmosphere). Based on previous work, the simple model presented in this thesis is then extended to include effects of CR diffusion into the Sgr B2 cloud parameterized by a "diffusion transport suppression" factor (and based on a molecular distribution – obtained from NH_3 spectral line emission studies – that can modeled as a three-dimensional Gaussian distribution). Our results show that the complex nature of the environment severely hampers the separation of the thermal and non-thermal emission so that no spectral, polarized or morphological evidence is found for non-thermal emission due to secondary electrons and positrons. Analysis of the radial brightness distribution from the centre of the main complex of Sgr B2 allowed us to place limits on the diffusion of GeV energy CRs into the cloud. This leads to a relative deficit of CRs at the centre of the cloud and a morphology which is reminiscent of a 'limb-brightening' of synchrotron emission from secondary electrons and positrons. This is in contrast to to the TeV energy γ-rays from which a good correlation with molecular matter in the GC region is observed. This is interpreted by us as evidence of the exclusion of GeV energy CRs from the densest molecular environments in this region, whilst the TeV (or higher) CRs are able to freely penetrate these regions leading to the γ-ray -molecular line emission correlation observed by the HESS telescopes.

Serendipitously, observations of this region uncovered evidence of non-thermal emission from a source to the south of the main complex of emission within Sgr B2. Analysis of archival *XMM-Newton* X-ray observations revealed an X-ray source located approximately $20''$ from the non-thermal radio source whose spectrum is strongly suggestive of a SNR. The non-thermal radio spectrum, X-ray source and spectrum were then used in concert with NH_3 line emission to argue that this source is a SNR of approximately 3000 years of age which had exploded in this dense region. A large gradient in the NH_3 line emission towards the X-ray source suggests that any SNR shell would expand towards this region of lower density. Analysis of higher resolution 1720 MHz ATCA data revealed a weak source whose extension is coincident with the X-ray source.

Finally, the observations of the Sgr B2 region were then expanded to explore the nature of the magnetic field amplitude on large scales in the region, of which there is a two orders-of-magnitude uncertainty. Based on earlier work, which showed a large $(6^\circ \times 2^\circ)$ region of synchrotron emission at the GC, we assembled single-dish and interferometric observations of this region. The objective of this was to explore the possibility that a 'spectral downturn' existed at GHz frequencies, which is due to the gradual dominance towards lower energies of the bremsstrahlung cooling rate over the synchrotron cooling rate. After the removal of appropriate background and the consideration of limitations at GeV and TeV energies, we found significant statistical evidence for a spectral break at $\sim$ 2 GHz, which implies a magnetic field amplitude of 100 μG in a density of $\sim$ 100 cm^{-3} . An amplitude this high, on such large scales will have a large impact on processes such as particle acceleration, star-formation and gas-dynamics in the region.

Disclosure

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. The author acknowledges that copyright of published works contained within this thesis (as listed below) resides with the copyright holder(s) of those works.

David I. Jones

Publications presented in this thesis

1. **Jones, D.I.**, Protheroe, R.J., Ekers, R.D., & Crocker, R.M., *Search for Synchrotron Emission from Secondary Leptons in Dense Cold Starless Cores*, 2008, PASA, 25, 161-166.

2. **Jones, D.I.**, Crocker, R.M., Protheroe, R.M., Ott, J. & Ekers, R.D., *Australia Telescope Compact Array Radio Continuum 1384 and 2368 MHz Survey of Sgr B.* Astronomical Journal submitted.

3. **Jones, D.I.**, Lazendic-Galloway, J., Crocker, R.M., Ekers, R.D. & Protheroe, R.J., *Non-thermal emission near Sgr B2: a new supernova remnant?* To be submitted to Astrophysical Journal.

4. Crocker, R.M., **Jones, D.I.**, Melia, F., Ott, J., & Protheroe, R.J., *Large Scale Magnetic Field Intensity of the Galactic Center Region.* Submitted to Nature.

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Publications not presented in this Thesis

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