Cloudy Ammonia: A multi-wavelength molecular line survey of the molecular clouds surrounding the W28 supernova remnant.

Brent Nicholas

B.Sc (Hons), Physics

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School of Chemistry & Physics

The University of Adelaide

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Abstract

This thesis is a multi-wavelength study of high energy objects interacting with the interstellar medium (ISM). One such object is the W28 supernova remnant (SNR) with several sites of TeV (10^{12} eV) γ-ray emission detected from its boundary by the H.E.S.S. telescopes. The γ-ray emission is spatially well matched to giant molecular clouds which surround the remnant. In order to understand the distribution of dense ($n > 10^3\,\mathrm{cm}^{-3}$) molecular gas in the region, multi-wavelength ($\lambda \sim$12 mm and 7 mm) molecular line surveys are presented. Utilising the NH_3, CS and SiO molecules, the broad-scale distribution of the dense and disrupted gas in the W28 region is revealed. Additional multi-wavelength data towards W28, including radio ($\lambda \sim$ cm), molecular line ($\lambda \sim$ mm), infra-red ($\lambda \sim 10^{-6}$ m), X-ray ($\lambda \sim 10^{-10}$ m) and γ-ray ($\lambda \sim 10^{-12}$ m) data, are compared and discussed in context with the results of this work. Other high energy ISM interacting objects, microquasars, are also studied. TeV γ-ray observations towards three candidate microquasars with jets and/or jet/ISM interactions are presented. In all three cases, no significant point-like or extended TeV γ-ray emission is seen and upper-limits are set.

Declaration of Originality

I, Brent Nicholas certify that 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. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

*Published works contained within this thesis:

Nicholas B., & Rowell G., 2008, American Institute of Physics (AIP) Conf. Proc., 1085, 245.

Nicholas B., Rowell G., Burton M.G., Walsh A., Fukui Y., Kawamura A., Longmore S. & Keto E., 2011, Monthly Notices of the Royal Astronomical Society (MNRAS), 411, 1367 (+ online appendices).

Nicholas B.P., Rowell G., Burton M.G., Walsh A.J., Fukui Y., Kawamura A. & Maxted N.I., 2011, Monthly Notices of the Royal Astronomical Society (MNRAS), *Accepted for publication. (24/08/2011).*

Nicholas B.P., Rowell G., Burton M.G., Walsh A.J., Fukui Y., Kawamura A. & Maxted N.I., *Manuscript in preparation.*

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Preface

Motivation

Two of the biggest unsolved questions facing modern high energy astronomers are, "What is the origin of cosmic rays?" and "How are they accelerated to such high energies?" These questions have remained unanswered for over a century, and finding the solutions to these age-old cosmic-ray (CR) problems were major driving forces behind the field of gamma-ray (γ-ray) astronomy. Very high energy (VHE) γ-rays ($E_\gamma > 100\,\mathrm{GeV}$, $1\,\mathrm{GeV}=10^9\,\mathrm{eV}$, $1\,\mathrm{eV} = 1.6\times10^{-19}\,\mathrm{J}$) are only produced in the most violent and extreme processes within the universe. With the exception of radioactive decay, VHE γ-rays are produced via interactions of accelerated charged particles, either hadrons (protons, α-particles, nuclei) or leptons (electrons, positrons). In the hadronic framework, γ-rays are the by-products of interactions between high energy hadrons, the so called cosmic-rays, while the leptonic framework is centred on the interactions of high energy electrons in photon and magnetic fields. Unfortunately, this also means that, until astronomers can determine the origin of the γ-rays, the origin of the multi-TeV ($1\,\mathrm{TeV} = 10^{12}\,\mathrm{eV}$) CRs will remain a mystery.

Along the Galactic plane, towards the Galactic centre, lies the W28 supernova remnant (SNR). The H.E.S.S. telescopes have detected several TeV γ-ray sources surrounding the remnant. These γ-ray sources spatially overlap with giant molecular clouds. W28 provides a unique laboratory to study both dense molecular gas and γ-ray emission. Studies of the gas and material toward sites of γ-ray emission are helpful in determining the origin of the γ-ray emission and can also provide information on the high energy particles which spawned them. Dense molecular gas provides a large target for CRs to interact with, which in turn, produce γ-rays in a hadronic manner. Not only does dense molecular gas provide evidence supporting a hadronic origin, it can also provide evidence against a leptonic origin. This makes studies of dense gas towards sites of γ-ray emission a powerful probe into the origin of the γ-rays and also provides information on the CRs in the region.

Within our Galaxy, the microquasar class of objects are candidate sources of TeV γ-ray emission. Relativistic 'jets', which manifest from the accretion powered system, are capable of accelerating particles to very high energies. Therefore, these VHE particle flows interacting with the interstellar medium (ISM) could provide another source of Galactic γ-ray emission, and another site of multi-TeV CR acceleration.

With these ideas in mind, this thesis is structured around a core theme of high energy objects, the W28 supernova remnant and several microquasars, which are interacting with the ISM.

Structure of this Thesis

This thesis is a multi-wavelength study of high energy objects interacting with the ISM. It tackles these issues from both the low energy end of the spectrum, by studying the dense molecular gas towards the W28 SNR, and the high energy end of the spectrum, with TeV γ-ray observations towards multiple ISM interacting microquasars.

Chapter 1 introduces the ISM, cosmic rays and the ideas of γ-ray astronomy in broad terms. Chapter 2 discusses the underlying physics of radiative transfer and discusses how molecular line observations are used to study dense gas. The ammonia molecule, which has been proven to be an exceptionally useful probe into the dense ISM, is discussed in detail. Chapter 3 introduces the Mopra millimetre wave telescope and presents the results of a 12 mm molecular line survey of the molecular clouds towards the W28 supernova remnant. Chapter 4 presents the results of a 7 mm molecular line survey of the molecular clouds towards the W28 supernova remnant. Chapter 5 presents the results of deep NH_3 observations of the disrupted molecular clouds towards W28. Chapter 6 discusses the underlying physics of ground based γ-ray astronomy, including the imaging atmospheric Cherenkov technique and the H.E.S.S. telescopes. The microquasar class of objects is also introduced and the results of γ-ray observations towards three microquasars interacting with the ISM are presented. Chapter 7 is a final summary of the work presented throughout this thesis and a brief outlook for future developments.

Public Displays of Results

The results of this thesis are submitted by publication. The work presented for this thesis, in various stages, has been presented at conferences and workshops around the world. Here I summarise the contributions of conference posters, conference proceedings and published works of which I have been a part.

- **Poster Submission:**
  H.E.S.S. Observations of the Microquasars Cir X−1, Cyg X−1 and 4U 1755−33, 2008, 4th Heidelberg International Symposium on High Energy Gamma-Ray Astronomy, Heidelberg, Germany.
  `http://www.mpi-hd.mpg.de/hd2008/pages/news.php`

- **Conference Proc:**
  H.E.S.S observations of the Microquasars Cir X−1, Cyg X−1 and 4U 1755−33, Nicholas B., & Rowell G., 2008, American Institute of Physics (AIP) Conf. Proc., 1085, 245.

- **Poster Submission:**
  Mopra NH_3 observations towards the TeV Supernova Remnant W28, 2009, International Winter School on the Interstellar Medium, Ise-Shima, Mie, Japan.
  `http://www.a.phys.nagoya-u.ac.jp/WS09/`

- **Poster Submission:**
  Mopra Studies of the dense gas towards W28 and RX J1713.7−3946, 2009, Astronomical Society of Australia - Annual Scientific Meeting, University of Melbourne, Melbourne, Australia.
  `http://asa2009.science.unimelb.edu.au/Site/Home_Page.html`

- **Poster Submission:**
  Mopra ammonia studies of the dense gas towards the supernova remnant W28, 2010, International Winter School on the Interstellar Medium, Ise-Shima, Mie, Japan.
  `http://www.a.phys.nagoya-u.ac.jp/WS10/`

- **Conference Presentation:**
  Deep Mopra studies of the dense and disrupted molecular gas associated with the TeV gamma-ray sources in the supernova remnant W28 field, 2010, Astronomical Society of Australia - Annual Scientific Meeting, University of Tasmania, Hobart, Australia.
  `http://www-ra.phys.utas.edu.au/ASA2010/`

- **Poster Submission:**
  Studies of the dense and disrupted gas towards the TeV gamma-ray supernova remnant W28, 2010, Great Barriers in High Mass Star Formation, Townsville, Australia.
  `http://www.jcu.edu.au/hmsf10/`

- **Refereed Journal Article:**
  12 mm line survey of the dense molecular gas towards the W28 field TeV gamma-ray sources, Nicholas B., Rowell G., Burton M.G., Walsh A., Fukui Y., Kawamura A., Longmore S. & Keto E., 2011, Monthly Notices of the Royal Astronomical Society (MNRAS), 411, 1367 (+ online appendices).

- **Refereed Journal Article:**
  A 7 mm line survey of the shocked and disrupted molecular gas towards the W28 field TeV gamma-ray sources, Nicholas B.P., Rowell G., Burton M.G., Walsh A.J., Fukui Y., Kawamura A. & Maxted N.I., 2011, Monthly Notices of the Royal Astronomical Society (MNRAS), *Accepted for publication. (24/08/2011).*

- **Poster Submission:**
  Deep NH_3 observations of the W28 supernova remnant TeV source HESS J1801−233, 2011, Astronomical Society of Australia - Annual Scientific Meeting, University of Adelaide, Adelaide, Australia.
  `http://www.physics.adelaide.edu.au/astrophysics/asa2011/`

- **Manuscript in Preparation.:**
  Deep NH_3 survey of the disrupted molecular cloud towards the W28 TeV gamma-ray source HESS J1801−233, Nicholas B.P., Rowell G., Burton M.G., Walsh A.J., Fukui Y., Kawamura A. & Maxted N.I., *Manuscript in preparation.*