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

Brent Nicholas
B.Sc (Hons), Physics

Submitted in total fulfilment of the requirements of the degree of Doctor of Philosophy

July 7, 2011

School of Chemistry & Physics
The University of Adelaide
Contents

List of Figures v
List of Tables vii
Abstract ix
Declaration of Originality xi
Preface xv
Motivation ....................................................... xv
Structure of this Thesis ....................................... xvi
Public Displays of Results ...................................... xvi

1 Introduction 1
1.1 Introduction ................................................. 1
1.2 The Interstellar Medium ..................................... 4
1.3 The Process of Forming Stars ................................. 4
1.4 Cosmic Rays ................................................... 8
1.4.1 Charged Particle Acceleration ............................ 10
1.5 \(\gamma\)-Ray Astronomy ......................................... 12
1.6 VHE \(\gamma\)-Ray Production .................................... 13
1.6.1 The Hadronic Emission Mechanism ..................... 14
1.6.2 Leptonic Emission Mechanisms ......................... 15
1.7 The Connection between Hadronic \(\gamma\)-Ray Emission and
Dense Molecular Gas ........................................... 16
1.8 Sources of VHE \(\gamma\)-Rays .................................... 17
1.8.1 Galactic Sources ......................................... 17
1.8.2 Extra-galactic Sources .................................. 20
1.9 The W28 Supernova Remnant ................................ 20
1.10 Multi-Wavelength Observations .................................. 23

2 Radiative Transfer Fundamentals ................................... 25
2.1 Equation of Radiative Transfer ..................................... 26
  2.1.1 Brightness Temperature from a Black Body ................. 28
2.2 The Detection Equation ............................................. 29
2.3 Molecular Line Radiative Transfer ................................. 30
  2.3.1 Level Populations ............................................. 30
  2.3.2 The Einstein Coefficients .................................... 31
2.4 Typical Molecular Species Used to Study Molecular Clouds .... 33
2.5 Physical Gas Parameters from Observations ..................... 34
  2.5.1 Optical Depth ............................................... 35
  2.5.2 Column Density .............................................. 36
  2.5.3 Temperature from the LTE Approximation .................. 38
2.6 The Ammonia Molecule ............................................. 38
  2.6.1 Introduction to the NH$_3$ Molecule ......................... 39
  2.6.2 The Ammonia Spectrum ...................................... 40
  2.6.3 Physical Gas Parameters from Ammonia Observations ...... 43

3 12 mm Molecular Line Observations Toward the TeV $\gamma$-Ray Sources in the SNR W28 Field ............ 51
  3.1 The Mopra Telescope ............................................. 51
    3.1.1 Mopra Construction ....................................... 51
    3.1.2 The Mopra Spectrometer MOPS ............................ 52
    3.1.3 The Mopra Receivers ...................................... 53
    3.1.4 Observing Modes .......................................... 54
    3.1.5 Calibration of Mopra Data ................................ 55
  3.2 Reducing Mopra Single Dish Data ............................... 56
    3.2.1 Reducing Position Switched Data ......................... 57
    3.2.2 Reducing On-The-Fly Mapping Data ....................... 57
    3.2.3 Further Data Processing .................................. 59
  3.3 Other Contributing Telescopes ................................ 60
  3.4 Results of 12 mm Mopra Observations towards the W28 Supernova Remnant ......................................... 64

4 7 mm Molecular Line Observations Toward the TeV $\gamma$-Ray Sources in the SNR W28 Field .............. 65
List of Figures

1.1 The Earth’s atmospheric transparency to EM radiation .................. 2
1.2 The Crab Nebula in multiple wavelengths .............................. 3
1.3 The Galactic Centre in multiple wavelengths .......................... 3
1.4 The Orion Nebula ....................................................... 7
1.5 The evolution of high mass stars ........................................ 9
1.6 Victor Hess in 1912 ..................................................... 10
1.7 The local cosmic ray spectrum .......................................... 11
1.8 A schematic of particle acceleration across a shock .................. 12
1.9 A skymap of the current TeV γ-ray sources ........................... 19
1.10 The mixed morphology supernova remnant W28 ...................... 21
1.11 The spatial overlap between molecular clouds and the TeV γ-ray emission towards W28 .................................................. 22
1.12 The γ-ray spectrum from an entire cloud vs. the dense core ..... 23
2.1 Radiative transfer through an isothermal medium .................... 27
2.2 A schematic of the NH$_3$ molecule .................................. 39
2.3 The energy levels of NH$_3$ ............................................. 42
2.4 The hyperfine structure of NH$_3$ (1,1) .................................. 44
3.1 The Mopra millimetre wave telescope .................................. 52
3.2 A schematic of the MOPS band set-up .................................. 53
3.3 Mopra radiation sources .................................................. 55
3.4 Forming the quotient spectra ............................................. 57
3.5 Livedata and Gridzilla data flow ........................................ 58
3.6 Locations of telescopes around the world ................................ 63
6.1 The development of an electromagnetic EAS ........................... 71
6.2 The development of a hadronic EAS .................................... 73
6.3 Monte Carlo simulation of an EAS initiated by a 300 GeV γ-ray and a 1 TeV proton ................................................................. 74
List of Tables

1.1 Typical physical parameters associated with GMCs 4
1.2 Cooling times associated with γ-ray production 16
1.3 Confirmed VHE γ-ray sources by source type 18

2.1 The primary molecules used to study molecular clouds 35
2.2 NH$_3$ satellite line intensities 45

3.1 Bandwidth of the Mopra receivers 53
3.2 Properties of the Mopra receivers 54
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 ($n > 10^3$ 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:


BRENT NICHOLAS

July 7, 2011
I would like to thank my principle supervisor, Gavin Rowell, for all his help and guidance over the past three and a half years. His advice and support at all stages of my PhD has been greatly appreciated. I am very appreciative of the funding Gavin secured, which enabled me to travel to conferences and workshops, both interstate and internationally, on multiple occasions. I thank my co-supervisor, Roger Clay, who provided a keen eye when proof reading this work. His ability to find time in his busy schedule and to provide extremely prompt feedback and advice when requested was a real asset, especially in the late stages of my thesis write-up. I extend my gratitude to my two un-official co-supervisors, Michael Burton (University of New South Wales) and Andrew Walsh (James Cook University), for providing help and support with the millimetre side of this project. Their vast knowledge and experience helped provide a smooth transition from γ-ray astronomy to radio and millimetre wave astronomy. Without their continued support, my research and progress would have definitely been slow-moving. I am indebted to Clive Moore and Chris Jordan who offered to proof read this work. Your fresh sets of eyes picked up corrections I overlooked and helped to improve this thesis.

I would also like to thank the post graduate students from the Adelaide University Astrophysics Group, both past and present, who helped keep my PhD experience positive and provided many interesting lunch-time conversations. I further extend my thanks to my office mate, Nigel Maxted, who provided many relevant discussions which kept my research moving forward. I acknowledge the support of the University of Adelaide and the School of Chemistry and Physics for the financial assistance of a Divisional Scholarship, and for extending its length beyond the initial three years.

Finally, my gratitude goes to my families and friends. I especially thank Charles and Nera Cox for looking after me and providing me with many lunch-packs, which fuelled my daily research. I thank my parents, Jayne and Lynton Nicholas, for all their support during my extended stay in the student lifestyle and Granny Dawn, who made sure this thesis was completed. Last, but certainly not least, I extend my love and gratitude to Ann-Marie Cox, who continually loves, supports, and makes me happy.
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 (\(E_\gamma > 100\ \text{GeV}\), \(1\ \text{GeV}=10^9\ \text{eV}\), \(1\ \text{eV} = 1.6\times10^{-19}\ \text{J}\)) 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 TeV = \(10^{12}\ \text{eV}\)) 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 \( \gamma \)-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 \( \gamma \)-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 \( \gamma \)-ray observations towards multiple ISM interacting microquasars.

Chapter 1 introduces the ISM, cosmic rays and the ideas of \( \gamma \)-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 \( \text{NH}_3 \) observations of the disrupted molecular clouds towards W28. Chapter 6 discusses the underlying physics of ground based \( \gamma \)-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 \( \gamma \)-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 proceed-
nings and published works of which I have been a part.

- **Poster Submission:**

- **Conference Proc:**

- **Poster Submission:**

- **Poster Submission:**

- **Poster Submission:**

- **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.
• 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.

• Refereed Journal Article:

• Refereed Journal Article:

• Poster Submission:

• Manuscript in Preparation.:  