

Radio afterglows of Gravitational Waves

Daniele d'Antonio

School of Mathematical and Physical Sciences
Faculty of Science
University of Technology Sydney
NSW - 2007, Australia

Radio afterglows of Gravitational Waves

*A thesis submitted in fulfilment of the requirements
for the degree of*

Doctor of Philosophy
in
Astrophysics

by

Daniele d'Antonio

to

School of Mathematical and Physical Sciences
Faculty of Science

University of Technology Sydney
NSW - 2007, Australia

December 2022

COVID-19 STATEMENT

The research project presented in this thesis has been impacted by Covid-19. Because of the pandemic, international and national conferences were not held in person. I was hence not able to expand my network of researchers and build up new collaborations.

Moreover, the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo suspended their observations in 2020. As a consequence, the PhD project has been repositioned by modifying the methodology and research topic. The project was originally supposed to be a study on radio transients with a particular focus on gravitational wave events. However, a study of variable galactic nuclei was inserted and the study of gravitational waves was from a more theoretical approach.

During the pandemic, Australian borders were closed and universities in Australia fired part of their staff as the number of international students dramatically decreased in 2020 and 2021. In those uncertain times, my main supervisor, Martin Bell, decided to resign from his position as a researcher at the University of Technology, Sydney. He decided to leave research and start a career as a data scientist at the University of Newcastle. During the year 2022, I never met with my supervisor in person and all our meetings were held online. He did everything possible to give me support and proper supervision. Nevertheless, remote supervision clearly made this PhD project more challenging.

ABSTRACT

This thesis describes a study of the research conducted by myself during these years as a PhD candidate working at the University of Technology, Sydney (UTS) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The thesis is divided in two main parts: the first part is comprised of research analysing the radio variable sky with a *classical* approach while the second part proposes the usage of statistical techniques poorly used in Astrophysics at the moment of writing this work.

Firstly, a comprehensive description of the instrumentation which has involved my research work. The instrumentation consists in the Australia Telescope Compact Array (ATCA), The Australian Square Kilometre Pathfinder (ASKAP), the Swift Gamma-ray Burst Explorer (*Swift*), the High Energy Stereoscopic System (HESS) and the two Michelson interferometers the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo. Principles of radio astronomy observations are also reported.

Secondly, a transients follow-up with the Australia Telescope Compact Array is presented. The research project comprised the study of the gamma-ray burst GRB190114c, the two flare stars AT Mic and UV Ceti. The investigation has been carried out by using the Rapid Response Mode. This modality consists in triggering radio telescopes as soon as a transient is detected by X-ray and gamma-ray telescopes. The analysis of the gamma-ray burst revealed possible scintillation while the flare stars activity could be due to gyrosynchrotron radiation, electron cyclotron maser or plasma radiation. Furthermore, campaign for detecting ultra-cool dwarfs (UCDs). These objects are hardly detectable and at the time of writing this work, only 25 sources were detected. The campaign is based on searching for objects with photometric variability and fast rotation. The search allowed to detect at least 3 objects from 11 radio observations.

Moreover, a study of variable active galactic nuclei (AGN) using the Australian Square Kilometre Pathfinder (ASKAP) is outlined. This research has been conducted with a targeted approach by selecting ASKAP sources listed in AGN catalogues. The study showed the detection of 30 variable AGN. The most likely explanation for their radio variability is scintillation because of the brightness temperature values above the Compton catastrophe limit of 10^{12}K .

Finally, the second part of this thesis is an analysis of innovative methods for studying variable and transient sources in Astrophysics. The work involves the study of light curves by using statistical methods named State Space Models. These models can be used for detecting a transient source hosted by a variable active galaxy. In this thesis, a method for detecting a gravitational waves event hosted by a hypothetical active galaxy

is explained. In addition, State Space Models can also encode several properties in light curves, such as slope, rise or decline for a given time t .

The conclusions of this thesis summarise the main results and the possible developments of the research projects described in the other chapters.

The thesis also contains an appendix showing fragments of the code used for testing State Space Models on astronomical time series data.

AUTHOR'S DECLARATION

I, *Daniele d'Antonio* declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the *School of Mathematical and Physical Sciences, Faculty of Science* at the University of Technology Sydney. This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program and the Australian Research Council.

Production Note:
SIGNATURE: Signature removed prior to publication.

[Daniele d'Antonio]

DATE: 16th December, 2022

PLACE: Sydney, Australia

DEDICATION

To my parents and my sister
Ai miei genitori e mia sorella

ACKNOWLEDGMENTS

I feel like I started this PhD yesterday. I still remember how I was feeling my first day at UTS. How nervous I was! I could not wait to start this journey! The first time I stepped into Martin's office to talk about my project I could not be more excited! However, everything comes to an end and here I am writing this section and having a final look at this thesis after three years and half of being a PhD student in Sydney. Time flies!

During these years, my supervisor Martin Bell, has always been a good fella. He assisted me not just on research but also on life in general. Martin, thank you for all our chats. Thank you for checking on me and for sharing your life experience when I broke up with my ex girlfriend. Besides, I will never forget how you did anything possible to supervise me even when you were no longer in Sydney. You didn't even get paid to supervise me anymore but you kept helping me whenever I needed. Maybe I could go to Newcastle and see you for a beer after submitting this thesis!

I'd like to thank also the great researchers I worked with in Australia such as Gemma Anderson who gave me the opportunity to explore the world of gamma-ray bursts and flare stars. It was great to chat with you in person in Narrabri. What a pity that the pandemic made that to be our first and last meeting in person. Thanks to Vanessa Moss who assisted me when I worked at CSIRO and when I had to deal with ATCA observations. You were so easy going and friendly since our first chat! I will always remember our chat about my future, when we talked about a career in research or industry. I also remember when you introduced me to Matthew Bailes. Thanks for everything you have done!

I want to thank Tara Murphy as well. It's been exciting to work in your research group and learn about radio and variable transients. Thanks for your efforts on granting me a PhD stipend during these years. Without those funds my PhD would not be possible. A thing I always appreciated of you is that you are always clear and direct on giving feedback and comments. This makes you tough sometimes but also honest.

I also want to thank James Brown who assisted me on the last two chapters of this

thesis and also made our meetings nice with our funny chats. Your comments were useful and precise but at the same time you helped me to understand that researchers shouldn't take themselves too seriously sometimes!

I can't not mention the people I came across these years at UTS. PhD means years of work but also fun. I shared my office with several people and I can't forget of Aishwarya whose the name still worries me when I have to write it. Now, I hope I wrote it well (damn! why didn't I give her a short easy nickname these years???). Thanks for being my main mate at the office. Thank you Trudy for being there and stand me whenever you came to the office. Natalia, thank you. You did not spend much time with us at UTS but those six months together have been amazing! Virginia, thanks for your company as well. Thanks to Luca who has been one my best friends. I missed you when you left UTS. We had good fun together. Thank you Matias and Tom for the nice time we spent together!

Thanks to Clara and Gioacchino who learnt all my PhD drama stories in these years! Coogee life wouldn't be the same without the two of you! Thank you Arnolda for our friendship! How crazy is the way we met in Sydney!? These years would not have been the same without you!!! Giulia and Christian also deserve a mention here. You guys helped me a lot on starting a life in Sydney!! Living with you guys has been great! You guys are the only flatmates I wouldn't get tired of! Giulia, the story our friendship is just great! That's amazing how we met at university in Italy and then re-met here in Sydney. It's true I followed you though (ahahaha).

Thank you Jessie. You just came to my life but you already mean a lot to me. You made this final stage of my PhD life a wonderful time. I feel soooo lucky I met you.

Finally, I really want to thank my parents mamma and papa', my sister and zio Remo for being always supportive and helpful during these four years in Australia. We were far but at the same time close, especially when I had just arrived in this country and I was alone on the other side of the World. My family always supported me in every decision since I was born. They indeed supported me when I decided to become an astrophysicist. I couldn't ask for a better family!

TABLE OF CONTENTS

List of Figures	xv
List of Tables	xxiii
1 Introduction	1
1.1 Preface	1
1.2 Instrumentation	2
1.2.1 The Australia Telescope Compact Array	2
1.2.2 The Australian Square Kilometre Array Pathfinder	11
1.2.3 Swift Gamma Ray Burst Explorer	21
1.2.4 High Energy Stereoscopic System	24
1.2.5 LIGO and Virgo detectors	24
1.3 Outline of science chapters: studying radio transients and variables	27
I Part I	31
2 Transients follow-up with the Australia Telescope Compact Array	33
2.1 ATCA Rapid-Response and Monitoring Follow-up of TeV Gamma-ray Bursts	34
2.1.1 Gamma-ray bursts progenitors and classification	34
2.1.2 Gamma-ray emission	35
2.1.3 X-ray emission	36
2.1.4 Radio emission	36
2.1.5 GRB mechanism	36
2.1.6 ATCA Rapid Response Mode	37
2.1.7 The necessity of a rapid radio follow-up of GRBs with the ATCA .	38
2.1.8 Detection of GRB190114C	38
2.1.9 Radio observations and data reduction	39
2.1.10 Results and discussion	39

TABLE OF CONTENTS

2.2	ATCA Rapid response of flare stars	42
2.2.1	Introduction	42
2.2.2	High energy emission	42
2.2.3	Radio emission	42
2.2.4	The necessity of a rapid radio follow-up of flare stars with the ATCA	43
2.2.5	Detection of AT Mic and UV Ceti	44
2.2.6	Radio observations and data reduction	45
2.2.7	Results and discussion	45
2.3	Uncovering the population of radio ultra-cool dwarfs	48
2.3.1	Introduction	48
2.3.2	Unresolved issues	48
2.3.3	Method of investigation and initial results	49
3	Radio variability of active galactic nuclei in the VAST pilot survey	53
3.1	Introduction	53
3.2	Data	55
3.2.1	ASKAP Data	55
3.2.2	AGN catalogues	56
3.3	Sample selection	58
3.3.1	Catalogues cross-matching technique	59
3.3.2	Variables selection method	59
3.4	Results	62
3.4.1	Variables and their classification	62
3.4.2	Explanation of the radio variability	63
3.4.3	Scintillation as a function of Galactic latitude	64
3.4.4	Single source analysis	70
3.5	Discussion and conclusions	70
II	Part II	77
4	Modelling time series in Astrophysics	79
4.1	Why State Space Models?	80
4.2	The first gravitational waves source observed by telescopes: GW170817	82
4.2.1	The discovery of gravitational waves	82
4.2.2	Electromagnetic emission models of GW170817	84

4.3	An alternative way for time series analysis in Astrophysics: State Space Models	87
4.3.1	The current method for time series analysis	87
4.3.2	Introduction to State Space Models	90
4.3.3	Fitting GW170817 radio light curve with State Space Models	91
4.4	Conclusions and possible developments	108
5	Using State Space Models for detecting gravitational waves	111
5.1	The case of the fast radio burst FRB 50418	112
5.2	Detecting a gravitational waves event in a simulated host active galaxy .	114
5.2.1	Conditions and scenarios for detecting transients within an active galaxy	114
5.2.2	Using State Space Models for detecting transient signals	116
5.2.3	Change points search in time series	119
5.3	Conclusions	124
6	Conclusions	125
6.1	Main thesis findings and future research	125
6.1.1	Gamma-ray burst GRB190114C investigation	125
6.1.2	A flare stars study	126
6.1.3	Radio variable AGN in VAST-P1 and RACS	127
6.1.4	State Space Models in time domain astronomy	128
A	Appendix	131
A.1	State Space Models in Python	131
	Bibliography	139

LIST OF FIGURES

FIGURE	Page
1.1 Five of the six antennas of the Australia Telescope Compact Array (Narrabri, New South Wales, Australia). Credit: Wilson et al. (2011).	3
1.2 Graph of a Cassegrain radio telescopes. Credit: S.T. Myers ¹	4
1.3 Representation of two antennas tracking a source with position vectors and baseline. The source is the outline on the celestial sphere. Credit: Thompson et al. (2017) . . .	5
1.4 (u,v)-coverage of an interferometer set out in a logarithmic spiral pattern comprised of 2, 5, 10 and 5 antennas (top to bottom) and observing for 10 seconds, 2, 4, and 6 hours (left to right). Credit: Avison & George (2012).	7
1.5 Geometry of a source with intensity $I(l, m)$ with an interferometer where the baseline vector has components (u, v, w) . Credit: Thompson et al. (2017)	8
1.6 Mapping the celestial sphere onto one image plane in one dimension. The point C is the field centre. The position of the point P is estimated with the direction cosine m with respect to the v axis. The projection into a plane surface P appears in P' with a distance from C which is proportional to $\sin\phi$. Credit: Thompson et al. (2017)	9
1.7 Radio spectrum of interference for the years 2011, 2015 and 2018 in the 16cm band from the ATCA User Guide. The different colours refer to different sources of the signal which are reported at the top of the graph.	10
1.8 RFI in 15mm band from the ATCA User Guide. The interference is evident from the three high peaks.	12
1.9 The Australian Square Kilometre Array (ASKAP). Credit: Hotan et al. (2021). . . .	13
1.10 Sensitivity profile over the field of view of ASKAP. The data were obtained with a 1.05 deg beam pitch and a centered frequency of 888 MHz. Credit: Hotan et al. (2021). . . .	15
1.11 Overview of the ASKAP systems (Hotan et al., 2021).	17

¹<http://www.aoc.nrao.edu/~smyers/Synth2004/MyersPolarization04print.pdf>

LIST OF FIGURES

1.12	Footprint of VAST-P1 with the number of observations for each field. There is also the VAST-P2 mid-band footprint (green regions). The sky map is based on J2000 equatorial coordinates in the Mollweide projection. The background is based on diffuse Galactic emission at 887.5 MHz modelled by Price (2016) and Zheng et al. (2016). Credit: Murphy et al. (2021).	19
1.13	Graph of the <i>Swift</i> satellite with its components. Credit: NASA.	22
1.14	The High Energy Stereoscopic System. Credit: Credit: webpages of HESS. ²	24
1.15	Simple graph explaining how a Michelson interferometer works. A laser beam is splitted in two beams though a Beam-splitting mirror. Each beam is directed to a mirror and then come back to the Beam-splitting mirror. Credit: ScienceNews ³	26
1.16	The LIGO Hanford (left) and LIGO Livingston (right) interferometers.	26
1.17	The Virgo interferometer.	27
2.1	Representation of the GRB mechanism. (Credit: earthsky.org ⁴).	37
2.2	Light-curve of GRB190114C.	41
2.3	AMI-LA 13-18 GHz (blue circles) and Swift WT/PC (green diamonds/orange squares) 0.3-10 keV light curves on a logarithmic scale. For clarity, error bars are not plotted but for both radio and X-ray data are typically ≤ 15 per cent. In X-rays the source was brightest at the first measurement, two minutes after the initial trigger, and then declined for around the first hour, re-brightening somewhere between 0.075 and 0.125 d. The radio flux (in blue) behaved similarly, with a bright, strong detection in the first measurement at 6 min, followed by a decline and subsequent rebrightening. A second, clearly resolved, radio flare occurred at around 1.1 d. By about four days the radio flux had settled down to a quiescent level of a few mJy. Credit: Fender et al. (2014).	43
2.4	VLA light curve of a giant radio flare seen from the dMe EV Lac. Each tick corresponds to 10 s and the inset shows the variation in circular polarisation on 5 min timescales during the flare decay phase. Credit: Osten et al. (2005).	45
2.5	Light-curve of AT Mic in 4cm band	46
2.6	Light-curve of UV Ceti in the 4cm band.	46
2.7	The collected literature detections and limits of UCD quiescent radio emission specific luminosity as presented by Pineda et al. (2017). Radio emission in Ultra-cool dwarfs (UCD) is rare.	49

²<https://www.mpi-hd.mpg.de/hfm/HESS/>

³<https://www.sciencenewsforstudents.org>

⁴<https://earthsky.org/space/>

2.8	Top - Preliminary light curve in the 5.5 GHz band binned at 36s for ATCA test observations of J2228-4310, revealing bursts in Stokes V and Stokes I. Bottom - Same as top, but for the 9 GHz band, partly contaminated by RFI, and showing a spectral dependence to the polarized burst emission. Credit: Sebastian Pineda.	50
3.1	Log scale modulation index (percentage) vs. χ^2 of all the 422 155 VAST-P1 sources obtained from the sample selection (see Section 3.3). The histogram on the top is the χ^2 distribution while the histogram on the right is the modulation index distribution. The red sources are the non-variable AGN of our sample. The yellow star-like objects are the variable AGN. Sources in the top-right quadrant are variable candidates. . .	61
3.2	Modulation index (percentage) vs. χ^2 plot of all the 4008 AGN from this study that are found in VAST-P1. We divided the AGN per class. Both steady objects and variables are reported. The variable AGN are the star-shape markers in the graph. The biggest star-shape markers indicate the high variable AGN. The vertical and the horizontal black lines delimit the threshold values of modulation index and χ^2 for selecting variables.	63
3.3	Histogram of the timescale that we estimated for every variable. Most variable AGN show variability in a time interval between 1 and 9 days.	65
3.4	Distribution of brightness temperature values (logarithm scale) of the sample of variable AGN. The values above 10^{12} K show that the variability is due to scintillation.	65
3.5	Modulation index vs. timescale. In these two plots we have the modulation index values predicted by the scintillation model, as well as the observed modulation index values. The orange and red triangles are the observed data (plot on the top). Most sources have modulation indices below the predictions (red triangles pointing down). Four objects have observed modulation indices values larger than the predicted ones (orange triangles pointing up). Objects with the grey tick-up are high variables. The plot on the bottom shows the objects by class. All variable BL Lacs have modulation index values below the predictions.	67
3.6	Measured timescale vs. Predicted timescale. Objects on the green line have a measured timescale consistent with the predicted one. For objects below the green line, the predicted timescale is longer than the observed one. For objects above the line, the opposite is true. The objects with the grey tick-up are highly variables.	68
3.7	Radio images of the 6 high variable AGN. Each source is in the centre of its radio image. VAST 090626.8+033311 is a Seyfert galaxy while the other plotted sources are QSOs.	72

LIST OF FIGURES

3.8	Light curves of the variable AGN. The black points are Selavy measurements while the red triangles are forced measurements.	73
3.8	(continued) Light curves of the variable AGN. The black points are Selavy measurements while the red triangles are forced measurements.	74
3.8	(continued) Light curves of the variable AGN. The black points are Selavy measurements while the red triangles are forced measurements.	75
4.1	Images cutout from three radio telescopes: Giant Metrewave Radio Telescope (GMRT), Very Large Array (VLA) and Australia Telescope Compact Array (ATCA). The two black lines indicate the position of the gravitational waves source. Panels (a), (b) and (c) show images from August to September 2017. Panels (d), (e) and (f) show images from October 2017. The white ellipse in the lower right corner of each image is the synthesised beam. Credit: Mooley et al. (2018).	83
4.2	In each figure, the eye indicates the line of sight. Model (A) is a classical weak sGRB with an ultra-relativistic jet on-axis. Model (B) is a classical strong sGRB with an ultra-relativistic jet slightly off-axis. Model (C) is a mildly relativistic, wide angle, strong cocoon with a choked jet. Model (D) is a mildly relativistic, wide angle, weak cocoon with a jet coming out from the lobe. Credit: Kasliwal et al. (2017).	85
4.3	GW170817 radio light curve of the first 300 days. The data are scaled to 1.4 GHz given a spectral index $\alpha = -0.58$ ($S \propto \nu^\alpha$). The blue fitting line with the shaded uncertainties region is the power law from Dobie et al. (2018). Credit: Dobie et al. (2019).	88
4.4	Plot of the two variability parameters for the radio sources of the VAST Pilot Survey Phase I (Murphy et al., 2021). Sources in the yellow region are classified as variables. These variables exceed 2σ for each parameter distribution, fitting a Gaussian function. Credit: Murphy et al. (2021).	89
4.5	Local level model fitting GW170817 (Dobie et al., 2018). The black points (with their errors also in black) are data from Dobie et al. (2018). The blue line is the modelled fit of the light curve. Every modelled value at the time t is estimated based of the value of the previous modelled value at the time $t - 1$. Hence, the model is "one step ahead." The light blue area is the 95% confidence region. Obviously, the negative values included in the confidence region should be ignored.	92

4.6	Example of heteroscedastic data set (top) and homoskedastic data set (bottom). The two plots show the behaviour of residuals vs. a variable X. The residuals are the difference between the predicted values (red fitting) and the actual measurements. Credit: The Free Encyclopedia. ⁵	94
4.7	Autocorrelation function of GW170817 light curve.	95
4.8	Local Linear Trend Model fitting GW170817 (Dobie et al., 2018). The black points (with their errors also in black) are data from Dobie et al. (2018). The blue line is the modelled fit of the light curve. The light blue area is the 95% confidence region. Obviously, the negative values included in the confidence region should be ignored.	98
4.9	AR model in space state representation form (blue fitting and light blue confidence region) with GW170817 light curve (black points and black error bars).	100
4.10	ARIMA model in space state representation form (blue fitting and light blue confidence region) with GW170817 light curve (black points).	103
4.11	Autocorrelation function of the residuals from the Local Level Model. The blue area is the confidence region which is included in the interval $\pm 1.96\sqrt{N}$	105
4.12	Residuals vs. time for the Local Level Model.	105
4.13	Plot of the residuals fitted a normal distribution (black fitting).	107
4.14	Q-Q plot of the residuals.	107
5.1	Radio light curve at 5.5 GHz of the source (FRB 50418) within the galaxy WISE J071634.59–190039.2. Black crosses are ATCA observations, blue triangles JVLA observations, and red squares VLBA, e-MERLIN and EVN. Credit: Johnston et al. (2016).	113
5.2	GW170817 hosted by a faint AGN. The transient source is between 1000 and 1200 days of observations. The host galaxy is much fainter than the gravitational waves source. It is then simple to detect a transient source.	115
5.3	GW170817 hosted by a bright AGN. The transient source is between 1000 and 1200 days of observations. The brightness of the host galaxy is comparable the one of the transient. It is then very challenging to detect a transient source.	115
5.4	GW170817 hosted by a bright AGN. The transient source is between 1000 and 1200 days of observations. The mean brightness of the host galaxy is much lower than the one of the transient. However, there are a few measurements comparable to the ones of the transient.	116

⁵<https://en.wikipedia.org/wiki/Homoscedasticityandheteroscedasticity>

LIST OF FIGURES

5.5	GW170817 hosted by a bright AGN. The transient source is between 1000 and 1200 days of observations. However, the presence of the source is not evident as it is within a variable active galaxy.	117
5.6	Local Level Model fitting the light curve. The error bars were omitted to clearly show the model fitting the data.	118
5.7	SSARIMA(3,1,25) model fitting the light curve. The light blue region is the 95% confidence region. The error bars were omitted to clearly show the model fitting the data.	118
5.8	SSARIMA(3,0,0) model fitting the light curve. The light blue region is the 95% confidence region. The error bars were omitted to clearly show the model fitting the data.	119
5.9	Local Level Model compared to the mean flux density. The blue trend is the prediction of the Local Level Model while the black line is the level of the mean flux density of the light curve.	120
5.10	Example of change points in a time series. The change points are highlighted by the red vertical lines. The change points divides the time series into segments with different statistical characteristics (standard deviation in this case). Credit: webpages of Arc GIS Pro. ⁶	121
5.11	Illustration of sliding windows in time series. Credit: Aminikhanghahi (2016).	121
5.12	Illustration of two adjacent sliding windows in a given time series T . The dashed line is the signal. The two rectangles are two sliding windows covering a time interval $a \leq t$ and $b \geq t$, respectively.	122
5.13	Schematic view of the Window-based change point detection method. The time series on the top is the original signal, the one in the middle is the discrepancy curve and the one on the bottom is still the discrepancy curve where the peaks of the curve are highlighted. We have a change point for each peak of the discrepancy curve. Credit: Truong et al. (2020).	122
5.14	Change points location detected with the window-based method.	124
A.1	State Space Autoregression Model analysis.	132
A.2	Code for fitting State Space Autoregression Model on a time series.	133
A.3	AR model in space state representation form (blue fitting and light blue confidence region) with GW170817 light curve (black points and black error bars).	134

⁶<https://pro.arcgis.com/en/pro-app/2.9/tool-reference/space-time-pattern-mining/how-change-point-detection-works.htm>

A.4	Code for defining the LocalLinearTrend class which is used for Local Liner Trend Models and Local Level Models.	135
A.5	Matrices defining the Local Linear Trend Model.	135
A.6	Code for fitting the Local Level Model on a time series.	136
A.7	Local Level Model (blue fitting and light blue confidence region) with GW170817 light curve (black points and black error bars).	137

LIST OF TABLES

TABLE	Page
1.1 Observing features reported in the ATCA Users Guide.	4
1.2 Observing features of ASKAP from Hotan et al. (2021).	14
1.3 VAST observing capabilities. Some VAST-P2 parameters could be different when the survey is carried on. The VAST-P2 parameters which can change in future are the number of epochs, the minumum and maximum spacing and the image rms per epoch at 1296 MHz. These numbers are in italics. Credit: Murphy et al. (2021).	19
1.4 Observing capabilities of <i>Swift</i>	22
1.5 Observing capabilities of BAT.	23
1.6 Observing capabilities of XRT.	23
1.7 Observing capabilities of UVOT.	23
1.8 Observing capabilities of HESS. H.E.S.S. II refers to the biggest antenna of the array while H.E.S.S. I to the other four antennas. Credit: webpages of HESS. ⁷	25
2.1 Radio observations of GRB190114C with the ATCA.	40
2.2 Radio observations of AT Mic and UV Ceti with the ATCA. The flux calibrator PKS B1934-638 is reported as 1934-638.	47
2.3 Detection of ultracool dwarfs summary with name of the source, date of observation, and polarisation regime reporting 'yes' for detections and 'no' for non-detections.	51
3.1 The AGN catalogues used in this study, including the total number of sources per catalogue and the number of AGN for each class: FSRQs, BCUs, BL Lacs, QSOs and active galaxies. The class 'Active galaxies' contains Seyfert galaxies, LINERs and galaxies with nuclear H II regions.	57

⁷<https://www.mpi-hd.mpg.de/hfm/HESS/>

3.2	This table shows the sources in common among the AGN catalogues. Each number indicates how many sources there are in common between the catalogues in the corresponding row and column (e.g. KDEBLLACS and BZCat have 19 sources in common). KDE stands for KDEBLLACS and WIB stands for WIBRaLS2. All the numbers in this matrix, refer to sources found in VAST-P1.	58
3.3	χ^2 and flux density mean values of the 4006 AGN from this study that are found in VAST-P1. The χ^2 and flux density errors are the standard deviations of the mean. In this table the entire AGN sample is divided in two groups: blazars and non-blazar AGN. We also describe three classes of blazars (FSRQs, BL Lacs and BCU) and two classes of non-blazars (QSOs and Active Galaxies). The Active Galaxies class is composed of LINERs and Seyfert Galaxies. . . .	66
3.4	Proportion of variables in each AGN class and for the overall study, expressed as both a ratio and a percentage.	72
3.5	Main properties of the Véron and KDEBLLACS variable AGN. The KDEBLLACS AGN are in the last five rows. For each source we report the VAST-P1 name, spectral class, χ^2 value, modulation index and redshift.	76
4.1	The following statistical parameters for the Local Level Model are listed: Aikake Information Criterion (AIC), Bayesian Information Criterion (BIC), Hannan-Quinn Information Criterion (HQIC) and Heteroskedasticity (H). . .	97
4.2	The following statistical parameters for the Local Linear Trend Model are listed: Aikake Information Criterion (AIC), Bayesian Information Criterion (BIC), Hannan-Quinn Information Criterion (HQIC) and Heteroskedasticity (H).	99
4.3	The following statistical parameters are listed: Aikake Information Criterion (AIC), Bayesian Information Criterion (BIC), Hannan-Quinn Information Criterion (HQIC) and Heteroskedasticity (H). The model is an Autoregressive (p=2) State Space Model.	100
4.4	The following statistical parameters are listed: Aikake Information Criterion (AIC), Bayesian Information Criterion (BIC), Hannan-Quinn Information Criterion (HQIC) and Heteroskedasticity (H). The model is a State Space ARIMA (1,2,1).	102

4.5	Confidence region width of the five models adopted: Local Level Model (LLM), Local Linear Trend (LLT) Model, State Space AR(2) Model, SSARIMA (1,2,1) and SSARIMA(2,1,1) with missing values. The first data point over time was not included for estimating these parameters.	103
4.6	Statistical results of the four models adopted: Local Level Model (LLM), Local Linear Trend (LLT) Model, State Space AR(2) Model and SSARIMA (1,2,1). .	104
5.1	Statistical results of the four models tested: Local Level Model (LLM), Local Linear Trend (LLT) Model, State Space AR(3) Model and SSARIMA (3,1,25). .	117

