Radio Interferometric Studies of Cool Evolved Stellar Outflows

A dissertation submitted to the University of Dublin
for the degree of Doctor of Philosophy

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Trinity College Dublin, September 2013

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Declaration

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Summary

You should write a nice summary here...

A dedication if you wish...

Acknowledgements

Some sincere acknowledgements...

List of Publications

Refereed

1. **O'Gorman, E.**, Harper, G. M., Brown, J. M., Brown, A., Redfield, S., Richter, M. J., and Requena-Torres, M. A.
   "CARMA CO(J = 2 - 1) Observations of the Circumstellar Envelope of Betelgeuse"
   The Astronomical Journal, 144, 36 (2012)

2. Sada, P. V., Deming, D., Jennings, D. E., Jackson, B. K., Hamilton, C. M., Fraine, J., Peterson, S. W., Haase, F., Bays, K., Lunsford, A., and **O'Gorman, E.**
   "Extrasolar Planet Transits Observed at Kitt Peak National Observatory"
   Publications of the Astronomical Society of the Pacific, 124, 212 (2012)

3. Sada, P. V., Deming, D., Jackson, B. K., Jennings, D. E., Peterson, S. W., Haase, F., Bays, K., **O'Gorman, E.**, and Lundsford, A.
   "Recent Transits of the Super-Earth Exoplanet GJ 1214b"
   The Astrophysical Journal Letters, 720, L215 (2010)

Non-Refereed

1. **O'Gorman, E.**, & Harper, G. M.
   "What is Heating Arcturus' Wind?",
   Proceedings of the 16th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun. Astronomical Society of the Pacific Conference Series, 448, 691 (2011)

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1
Scientific Overview

Here is the introduction of the thesis, complete with a few references (Prothero & Buell, 2007; Sagan, 1997). Section 3.1 contains Equation 1.1, Section 3.2 has Figure 1.1 and Section 3.3 has Table 1.1. Chapter 2 has pretty much nothing in it.

1.1 First Section

This section has an equation. Here it is:

$$L_\odot = 4\pi R_\odot^2 \sigma T_e^4 \tag{1.1}$$

which is a nice way of describing the luminosity.

1.2 Second Section

So this section has a figure in it[1]. That figure depicts the basic structure of a red giant.

[1] And also a footnote.

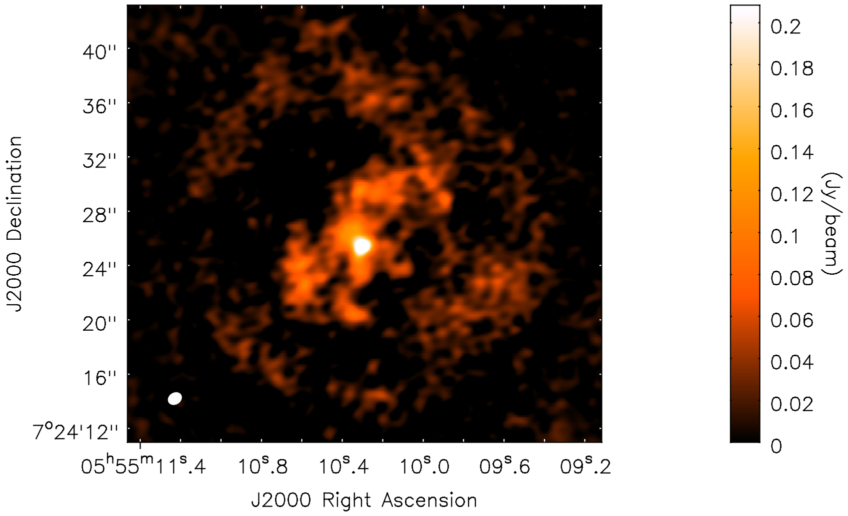

Figure 1.1: Red Giant and Asymptotic Giant Branch Stars. The left side of the figure shows the basic structure of a star on the giant branch of the HR diagram, while the right side shows a similar star after it has evolved to ascend the asymptotic giant branch. *Image Credit: Australian Telescope National Facility.*

1.3 Second Section

This section contains a basic table.

Table 1.1: Physical Properties of α Boo and α Tau.

Property	α Boo	α Tau	Reference
HD Number	124897	29139	...
Spectral Type	K2 III	K5 III	1, 2
ra (ICRS: ep=J2000)	$14^{\mathrm{h}}15^{\mathrm{m}}39.672^{\mathrm{s}}$	$04^{\mathrm{h}}35^{\mathrm{m}}55.239^{\mathrm{s}}$	3
dec (ICRS: ep=J2000)	+19 10 56.673	+16 30 33.489	3
pm-ra (mas yr^{-1})	-1093.39 ± 0.44	63.45 ± 0.84	3
pm-dec (mas yr^{-1})	-2000.06 ± 0.39	-188.94 ± 0.65	3
π (mas)	88.83 ± 0.54	48.94 ± 0.77	3
Distance (pc)	11.3±0.1	20.4±0.3	3
M ($M_{\odot}$)	0.8±0.2	1.3±0.3	6, 4
θ_{UD} (mas)	21.0±0.2	20.2±0.3	5
θ_{LD} (mas)	21.0±0.2	20.2±0.3	5
L ($L_{\odot}$)			
R ($R_{\odot}$)	25.4±0.3	44.4±1.0	...
Log g			
T_{eff} (K)	4294±30	3970±49	5
v_{rad} (km s^{-1})	$+5.19 \pm 0.04$	$+54.11 \pm 0.04$	9
v_{esc} (km s^{-1})	110	106	...
v_{∞} (km s^{-1})	∼40	∼30	7, 8
T_{wind} (K)	∼10,000	<10,000	7, 8
$\dot{M}$ ($M_{\odot}$ yr^{-1})	2×10^{-10}	1.6×10^{-11}	7, 8
H ($H_{\odot}$)			...

References.-(1);(2)Gray *et al.* (2006); (3)van Leeuwen (2007); (5)di Benedetto (1993); (6)Kallinger *et al.* (2010); (7)Drake (1985); (8)Robinson *et al.* (1998) (9)Massarotti *et al.* (2008)

2

Introduction to Radio Interferometry

The poor spatial resolution provided by a single dish radio antenna can cause difficulties in obtaining accurate flux density measurements of radio astronomical sources, especially at long wavelengths. A single dish radio antenna is unable to distinguish against background radio emitters located in the primary beam, and therefore the the observed flux density can contain emission from unrelated sources. This limitation can be overcome through interferometry. An interferometer acts as a spatial filter, and can discriminate against smooth backgrounds while its higher resolution allows seperation of the target from nearby confusing sources.

2.1 Radio Antenna Basics

The quality and properties of the final radio image produced from a synthesis array are partially dependent on the properties of the the individual antennae in the array. The most important such properties are discussed in the following sections and include aperture size, aperture efficiency, pointing accuracy, sidelobe level and noise temperature. We define the radio antenna as the piece of equipment which converts the electromagnetic waves emitted from the observed source into an electric current ready to be input into to the first low noise amplifier where the signal is at the radio/sky frequency, $\nu_{\rm RF}$.

2.1.1 Radio Antenna Formulae

The power gain of a transmitting antenna is a measure of the antenna's capability of converting power into radio waves in a specific direction. In radio astronomy, the receiving counterpart of transmitting power gain is the effective collecting area of an antenna, $A(\nu,\theta,\phi)$, where ν is frequency and θ and ϕ are direction coordinates. An ideal radio antenna would collect all incident radiation from a distant point source and convert it to electrical power. The total spectral power P_ν, collected by it would then be a product of its geometric area and the incident spectral power per area, or flux density F_ν. By analogy then, the effective area of a real radio antenna is defined

$$A(\nu,\theta,\phi) = \frac{P_\nu}{F_\nu} = \frac{P}{I(\nu,\theta,\phi)\Delta\nu\Delta\Omega} \tag{2.1}$$

where $I(\nu,\theta,\phi)$ is the source brightness in units W m^{-2} Hz^{-1} sr^{-1} that the antenna is pointing at and P is the power (in Watts) received by the antenna in bandwidth $\Delta\nu$ from element $\Delta\Omega$ of solid angle. The normalized antenna reception pattern $\mathcal{A}$, often referred to as the power pattern due to the duality between receiving and transmitting, is defined as

$$\mathcal{A}(\nu,\theta,\phi) = \frac{A(\nu,\theta,\phi)}{A_0} \tag{2.2}$$

where A_0 (m^2) is often referred to as the effective area of the antenna and is the response at the center of the main lobe of $A(\nu,\theta,\phi)$ [i.e. A(ν,0,0)]. Then the beam solid angle, Ω_A, of the primary beam is

$$\Omega_A = \iint_{\rm all\ sky} \mathcal{A}(\theta,\phi) d\Omega \tag{2.3}$$

and is a measure of the field of view of the antenna.

In the case of an isotropic antenna [i.e., $\mathcal{A}(\nu,\theta,\phi) = 1$], the product of the effective area and the primary beam solid angle is equal to the square of the wavelength (Kraus *et al.*, 1986)

$$A_0 \Omega_A = \lambda^2 \tag{2.4}$$

Ω_{A} has its maximum possible value of 4π if $\mathcal{A}$ is everywhere equal to 1. This means that the primary antenna can see the whole sky with equal sensitivity. Even though a large field of view is usually desirable in radio astronomy, Equation 2.4 ensures that for any given wavelength, when Ω_A is a maximum, the power received is a minimum and therefore the sensitivity is also at a minimum. To improve sensitivity, one could increase the collecting area of the antenna, but Equation 2.4 then ensures that the field of view must decrease. Thus, when deciding on the primary antenna size in a synthesis array, there is always a trade-off between field of view and sensitivity.

In reality, an antenna cannot radiate isotroptically and will radiate preferentially in one or more directions. A Fourier transform relationship exists between the complex voltage distribution of the field, $f(u, v)$, in the aperture of the antenna and the complex far-field voltage radiation pattern, $F(l, m)$, of the antenna (Kraus *et al.*, 1986)

$$F(l, m) = \iint_{\mathrm{aperture}} f(u, v) e^{2\pi i(ul+vm)} du dv \tag{2.5}$$

and

$$f(u, v) = \int_{\infty}^{\infty} \int_{\infty}^{\infty} F(l, m) e^{-2\pi i(ul+vm)} dl dm \tag{2.6}$$

The antenna power pattern, $\mathcal{A}$, is related to this radiation pattern by $\mathcal{A} = |F|^2$. The from of $f(u, v)$ is determined by the manner in which the antenna feed illuminates the aperture.

2.1.2 Antenna Structural Design

2.1.3 Antenna Performance Parameters

The geometric collecting area of a parabolic antenna, A_{geo} ($=\pi \mathrm{r}^2$) is related to the effective area, A_0, via the dimensionless quantity less than unity known as the aperature efficiency η

$$\eta = \frac{A_0}{A_{\mathrm{geo}}} \tag{2.7}$$

2.2 Fundamentals of Astronomical Interferometry

Young's Slits

2.3 The Synthesis Telescope

2.4 The Measurement Equation

3

Instrumentation and Observations

So this Chapter has nothing really, apart from a shout out to Appendix A, and maybe a few more sample references (Harper & Brown, 2006; Seaquist & Taylor, 1990).

3.1 CARMA

3.1.1 The Basic Instrument

3.1.2 The CARMA Electronic System

3.1.3 Observations

3.2 VLA

3.2.1 The Basic Instrument

3.2.2 The VLA Electronic System

3.2.3 Observation Preparation

3.2.4 Observations

3.3 GMRT

A
A Nice Appendix

This is where the appendix would go...

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