European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME — PERIOD: **101A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title — Category: **A–9**

This Is The Proposal Title This Is The Proposal Title

2. Abstract / Total Time Requested

Total Amount of Time:

This is a concise abstract of the proposal which may have up to 9 lines.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	101	FORS2	4h	may	n	0.8	PHO	s	

4.

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:	NTT	4n in 97.B-1234
b) still required to complete this project:	UT2	20h

5. Special remarks:

This macro is optional and can be commented out.

6. Principal Investigator: JSMITH999

6a. Co-investigators:

L.	Maçon	1098
R.	Menéndez	1098
S.	Bailer-Brown	1154
K.L.	Giorgi	1339

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale:

The case for AGN feedback: Determining how today's galaxies have grown and evolved to their present state is the primary goal of extragalactic research. It is now clear that galaxy growth is strongly regulated by so-called "feedback" processes (e.g., Vogelsberger et al. 2014, Schaye etal. 2015). Among the most important of these is the suppression of galaxy growth by Active Galactic Nuclei (AGNs) that heat and/or expel gas which would otherwise collapse to form stars (see Fabian, 2012; Harrison, 2017 for reviews).

The case for AGN feedback has recently received significant empirical support from observations. Firstly, X-ray observations of nearby clusters have revealed AGNs injecting considerable amounts of energy into the intergalactic medium, preventing it from cooling and forming stars (e.g., McNamara & Nulsen 2012). Secondly, there is clear evidence of fast (i.e., $>$ 500s km s^{-1}), ionised outflows in the optical and near-infrared spectra of a significant fraction (i.e., $\sim 20\%$; e.g., Mullaney et al. 2013; Harrison et al. 2014) of all AGNs. Both provide strong evidence of energy transport from AGNs, as required by feedback models. The problem we face, however, is that we do still not understand (a) how AGNs are triggered and (b) what mechanism drives the outflows that transport energy from the AGN. Until these questions are addressed, it will remain impossible to test whether AGN feedback is being accurately implemented in models of galaxy growth.

The role of IFU surveys in studies of AGN feedback: The key to determining how AGNs are triggered are spatially resolved kinematics of their host galaxies. This is because any triggering mechanism must funnel gas to fuel the AGN from galactic scales to the nucleus. Similarly, to determine how AGN outflows are driven requires spatially resolved observations of those outflows, mapped-out by their gas kinematics. Such spatially-resolved kinematics of the outflows and, in particular, the host galaxy can *only* be delivered by integral field (IFU) observations of *low redshift* (i.e., $z < 0.4$) AGNs.

To date, detailed IFU observations of nearby AGNs have almost exclusively focussed on radio-weak AGNs (e.g., the CARS survey [PI: Husemann]). However, **there is strong evidence of an association between fast, ionised outflows and radio-powerful AGNs**, with 50% of AGNs with 1.4 GHz radio luminosities ($L_{1.4\mathrm{GHz}}$) above 10^{23} W Hz^{-1} displaying evidence of powerful ($>$ 500 km s^{-1}) outflows, compared to just 10% of those below this radio luminosity threshold (Mullaney et al. 2013; Fig. 1, *left*). Furthermore, our own resolved long-slit and IFU observations of nearby radio AGNs show clear signs of interaction between radio jets and the ISM (e.g., Holt et al. 2008, Tadhunter et al. 2014, Santoro et al. 2015). This raises the prospect that jets launched from radio AGNs are an important driver of powerful gas outflows, as predicted by the hydrodynamical simulations of jet/gas interactions described in Wagner et al. (2011; Fig. 1 *right*; also Mukherjee et al. 2016). Furthermore, radio loud AGNs are the *only* type capable of inducing "radio-mode" AGN feedback, which is thought to heat intergalactic gas, preventing it from collapsing onto galaxies to form stars (e.g., Bower et al. 2006). Since radio powerful AGNs have largely been avoided by IFU studies, it is likely that they have ignored one of the most important drivers of AGN feedback. We now propose to address this with deep MUSE observations of two prototypical nearby radio AGN. As well as delivering excellent science in its own right, the proposed observations will form a feasibility study for a Large Programme, as recommended by the OPC in P101A.

B – Immediate Objective: We propose to obtain deep MUSE observations of two prototypical, nearby radio-powerful AGN to determine: **(a) how they are triggered** and **(b) what drives their outflows**. For (a) our own detailed morphological studies of the 2 Jy sample have revealed that tidal tails, fans, shells, and bridges – features commonly associated with galaxy mergers – occur far more frequently around powerful radio AGNs compared to luminosity-matched comparison early-type galaxies (94% of radio AGNs vs 50% of non-active early-types when of similar surface brightness; Ramos Almeida et al. 2011, 2012; Fig. 2). However, with both major and minor mergers capable of producing strong tidal features, it is not clear what type of mergers trigger radio AGN. Thankfully, stellar kinematics can be used to distinguish between the types of mergers that have taken place. Shallow, long-slit observations give provide tantalising, yet unconfirmed, evidence that radio AGNs are associated with fast rotators. If confirmed, his would connect powerful radio AGNs to major wet mergers, such as those that trigger ULIRGs. By contrast, should they instead be triggered by accretion of hot halo gas or minor mergers as suggested by some models (e.g., King & Pringle 2006; Hopkins & Quataert 2010), they would show a preference toward slowly-rotating early-type galaxies. **By mapping the stellar kinematics across the entire host galaxy, our MUSE observations will determine what type of galaxy interaction are required to trigger powerful radio AGNs**.

The Observations

In this section we highlight how our MUSE observations of the 2 Jy sample will build upon our current understanding of radio AGNs, enabling us to determine how radio AGNs are triggered, how their outflows are driven, and measure the properties and impact of these outflows.

How are radio AGNs triggered?: To establish what triggers radio AGNs demands detailed observations of their immediate surroundings, and in particular their host galaxies. Initial inspection reveals that the majority of radio AGNs reside in massive ($> 10^{11}$ M$_\odot$), early type galaxies (e.g., Matthews, Morgan & Schmidt 1964).

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

However, our own detailed morphological studies of the 2 Jy sample have revealed that features such as tidal tails, fans, shells, and bridges occur far more frequently around powerful radio AGNs compared to luminosity-matched comparison early-type galaxies (94% of radio AGNs vs 50% of non-active early-types when of similar surface brightness; Ramos Almeida et al. 2011, 2012; Fig. 2). This indicates a far more violent *recent* merger history than their early-type morphologies initially suggest.

The prevalence of tidal features around radio AGNs provides clear evidence that galaxy interactions play a role in triggering at least some powerful radio AGNs. However, with both major and minor mergers capable of producing strong tidal features, it is not clear what type of merger trigger radio AGN. Thankfully, stellar kinematics can be used to distinguish between the types of mergers that have taken place. Fast rotating early-type galaxies are produced by wet, major mergers, while slow rotators are thought to be produced by dry major or a series of minor mergers (Cappellari et al. 2016 and references therein).

To date, only a handful of radio AGNs have had their hosts' stellar kinematics measured, and even then only with long-slit spectra out to only a fraction of an effective radius (Smith and Heckman et al. 1990, Bettoni et al. 2001). These few shallow observations provide tantalising, yet unconfirmed, evidence that radio AGNs are associated with fast rotators. If confirmed, this would connect powerful radio AGNs to major wet mergers, possibly representing a post-starburst phase, since local Ultra Luminous Infrared Galaxies (ULIRGs) are also associated with fast rotation (e.g., Genzel et al. 2001; Tacconi et al. 2002). Should they instead be triggered by an alternative mechanism, such as accretion of hot halo gas or minor mergers as suggested by some models (e.g., King & Pringle 2006; Hopkins & Quataert 2010), they would show a preference toward slowly-rotating early-type galaxies. Finally, should radio AGNs show no preference to either fast or slow rotators, it would imply that the type of merger is not important, with either wet, dry, major or minor capable of triggering them. **By mapping the stellar kinematics across the entire host galaxy, our MUSE observations will determine what type of galaxy interaction are required to trigger powerful radio AGNs.**

With our MUSE observations, we will spatially resolve (to at least one effective radius) the host galaxies of all our sample. We will measure the off-nuclear stellar velocity shift (V) and velocity dispersion (σ) from stellar absorption lines. At the low redshifts of these sources, the MUSE spectra will cover the strong Mg$b\lambda5200$ absorption line, although we will fit the whole stellar continuum with gaussian-convolved stellar templates to maximise the information from the stellar continuum (i.e., excluding emission lines and using the Penalised Pixel-Fitting method of Cappellari & Emsellem, 2004). To extract just the first two velocity modes (i.e., V and σ) requires a comparitavely low continuum signal-to-noise of $\sim$10 (e.g., Cappellari et al. 2007). To ensure we measure the characteristic kinematics of the whole galaxy, rather than just the core, *it is vital that we reach this sensitivity to at least one effective radius* (a diameter of 20 kpc, or 20″ [4″] for our lowest [highest] redshift target). This can only be achieved with deep ($\sim$ 2 hr) observations (see Box 9).

We will use the criteria of Emsellem et al. (2007) to distinguish between fast and slow rotating early type radio AGN hosts. This uses the resolved V and σ maps to overcome some of the degeneracies associated with traditional V/σ measurements. Next, we will compare the relative numbers of fast and slow rotators in our sample against mass-matched samples of non-AGN early type galaxies from the Atlas^{3D} survey (Cappellari et al. 2011). Should our sample display a significant departure from the relative numbers of fast to slow rotators in this comparison sample, it would imply a preference of one over the other. We will also compare against the radio-weak AGNs targeted with MUSE as part of the Close AGN Reference Survey (CARS; PI: Husemann) to determine whether powerful radio AGNs show evidence of being triggered via different mechanisms compared to radio-weak AGNs. With 36 radio AGNs, our sample contains sufficient statistics to robustly test for this as a function of AGN type (broad line, narrow line, weak line) and luminosity, thereby demonstrating whether different classes of AGNs are triggered by different mechanisms.

What drives outflows from radio AGNs?: To have any impact on galaxy evolution, the energy from an AGN, radio powerful or otherwise, must be transmitted into their host galaxies or surrounding material *and* effect some influence. Our team has played a leading role in identifying fast, yet non-relativistic ($\sim$ 1000 km s^{-1}) winds associated with powerful AGNs (e.g., Tadhunter et al. 2001, 2014; Alexander et al. 2008; Villar-Martin et al. 2014, 2016; Harrison et al. 2014; Santoro et al. 2015; Spence et al. 2016; Figs. 3 & 4). These winds are often extended over kpc-scales, thereby *potentially* affecting a large fraction of the host galaxy as demanded by AGN feedback models (e.g., Alexander et al, 2008; Harrison et al. 2012, 2014; Tadhunter et al. 2014). Our investigations have also found that such winds are more prevalent among AGNs displaying evidence of nuclear radio emission. Indeed, our long-slit observations of a subsample of the 2 Jy sample has shown that some of the fastest AGN winds in the local Universe are associated with powerful radio AGNs (e.g., Tadhunter et al. 2016). As such, it is important for our models of feedback that we establish their primary driving mechanism, whether the radio jet or the intense radiation from the AGN. **Our MUSE observations will achieve this by mapping the winds in the 2 Jy AGN, allowing us to relate them to the resolved radio jets.**

By measuring the profiles of the strong forbidden [O III]λ5007 emission line, we will map the kinematics of the ionised gas in our sample. The [O III] line traces low density gas and has been used extensively in recent studies, not least our own, to successfully measure the kinematics and extent of outflows in AGN host galaxies. The

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: Provide here a careful justification of the requested lunar phase.

Time Justification: (including seeing overhead) Provide a careful justification of the requested number of nights or hours for each observing run here. ESO Exposure Time Calculators exist for all Paranal and La Silla instruments and are available at the following web address:
http://www.eso.org/observing/etc .
Links to exposure time calculators for APEX instrumentation can be found in Section 7 of the Call for Proposals.

8a. Telescope Justification:

Justification for the use of the selected telescope (e.g., VLT, APEX, etc...) with respect to other available alternatives.

8b. Observing Mode Justification (visitor or service):

Explain if a particular observing mode is specifically needed for this programme. If either can, in principle, be used then please enter N/A.

8c. Calibration Request:

Special Calibration - Adopt a special calibration

9. Report on the use of ESO facilities during the last 2 years

This macro is optional and can be commented out.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

Are the data requested in this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain the need for new data.

9b. GTO/Public Survey Duplications:

Specify whether there is any duplication of targets/regions covered by ongoing GTO and/or Public Survey programmes. If so, please explain the need for the new data here. Details on the protected target/fields in these ongoing programmes can be found at:
GTO programmes: http://www.eso.org/sci/observing/teles-alloc/gto.html
Public Survey programmes: http://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html
This macro is optional and can be commented out.

10. Applicant's publications related to the subject of this application during the last 2 years

Name1 A., Name2 B., 2001, ApJ, 518, 567: Title of article1

Name3 A., Name4 B., 2002, A&A, 388, 17: Title of article2

Name5 A. et al., 2002, AJ, 118, 1567: Title of article3

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	NGC 5139	13 26.8	-47 29	5.0	6.12	1 deg	Omega Cen	

Target Notes: A note about the targets and/or strategy of selecting the targets during the run. For APEX runs please remember to specify the PWV limits for each target under 'Additional info' in the table above.

12. Scheduling requirements

This proposal involves time-critical observations, or observations to be performed at specific time intervals.

3. Unsuitable period(s) of time

Run	from	to	reason
A	15-jul-17	18-jul-17	Insert explanation of unsuitable time here.

12. Scheduling requirements contd...

4. Specific date(s) for time critical observations:

Run	from	to	reason
A	12-may-17	14-may-17	Insert reason for time-critical observations.

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
101	FORS2	A	Detector	MIT
101	FORS2	A	IMG	ESO filters: provide list HERE

6b. Co-investigators:

...continued from Box 6a.

S.	Lichtman	1377