European Organisation for Astronomical Research in the Southern Hemisphere

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME

PERIOD: **103A**

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: **D–5**

The All-weather MUse Supernova Integral field Nearby Galaxies (AMUSING) survey IX: supernova and tidal disruption event rates as a function of environment age and metallicity

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 99 hours SM

The rate of extra-galactic transients (here core-collapse supernovae; CC SNe, and tidal disruption events) conveys critical progenitor information. In turn, the CC SN rate can be used to trace star formation. To date, such rates have been derived with respect to global host properties, such as galaxy type, colour, and mass, leading to suggestions of dependencies on progenitor age and metallicity. However, concrete conclusions are hampered by a) the nature of the transient-searches: historically targeted to large galaxies, and b) the limitations in global host characterisation using broad-band photometry. Here we will overcome these issues by using MUSE to observe the host galaxies of complete transient samples (CC SNe and tidal disruption events) from ASAS-SN. Rates will be computed with respect to spectroscopic environment properties, affording strong constraints on progenitor properties and how such rates vary as a function of initial star formation conditions.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	103	MUSE	89h	any	n	n	THN	s	
B	103	MUSE	10h	any	n	n	THN	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

This project is a ‘filler’ program, with targets across the full RA and DEC range, and that are observable in THN, bad seeing conditions, and during bright time. We understand that only part of the observations may be completed. This is a continuation of the AMUSING survey. Here, we investigate host galaxies of CC SNe and tidal disruption events, where the science case is distinct from previous semesters.

6. Principal Investigator: (moved to the CoI list)

6a. Investigators:

All CoIs moved to the end of the document.

7. Description of the proposed programme

A – Scientific Rationale: Core-collapse supernovae (CC SNe) are the explosive end points in the lives of most stars more massive than 8-10 $M_{\odot}$. Given their high optical luminosities, they can be observed throughout the Universe, making them strong tracers of massive star formation (SF). These explosions drive the chemical enrichment of the Universe, while their energetics are thought to play important roles in galaxy evolution. They are also the likely progenitors of neutron and/or black hole binary systems that eventually lead to kilonovae and gravitational wave events.

CC SNe display a wide diversity in light curve and spectral properties that is dependent on the pre-SN properties of the progenitor star (e.g. fraction of envelope mass retained, radius) together with the properties of the explosion (e.g. energy, ^{56}Ni mass). This pre-SN configuration is then dependent on the previous stellar evolutionary path taken by the progenitor, with the mass-loss process most likely dominating. Massive star mass loss can be in the form of steady winds, eruptions and mass transfer. Which of these processes dominates then depends on initial parameters such as the progenitor mass, metallicity, rotation and the presence/absence of a binary companion. One of the key goals of SN research is mapping ZAMS properties through stellar evolution to pre-SN progenitors and then to the transient phenomena we observe as SNe. Tidal Disruption Events (TDEs) are another flavour of extra-galactic transient that are thought to arise from stars being torn apart when passing close to supermassive black holes. These also display diversity that can be linked to the parameters of the stellar–black hole interaction.

Relative rates of different SN types can strongly constrain the massive star progenitor to CC SN transient sequence. For example, the ratio of SNe II (hydrogen rich) to 'Stripped Envelope' events (SE SNe, hydrogen poor; types IIb, Ib and Ic) informs how many massive stars have lost most of their outer envelopes prior to explosion. The relative number of CC SNe displaying narrow emission lines in their spectra (IIn, Ibn, Icn) - implying interaction of the SN ejecta with dense circumstellar material - constrains the rate at which massive stars suffer non-steady eruptive mass-loss. How these rates correlate with progenitor age and metallicity has strong implications for our understanding of massive star evolution. The overall rate of CC SNe with respect to host-galaxy/host-environment SF and metallicity is a key parameter in understanding mass ranges for successful explosions. Current CC SN explosion models suggest that a) successful explosions become more difficult as ZAMS mass increases, but b) that there may be 'islands of explodability' at higher masses where explosions are also possible. In non-successful explosions the majority of the star is not ejected but accretes onto the proto-neutron star eventually forming a black hole without a bright transient. Comparing the CC SN rate to the SF rate of galaxies/environments can strongly constrain such scenarios.

While there is a significant literature on SN/extra-galactic transient rates, to date these studies generally suffer from three significant issues: 1) the transients used are taken from historical searches that are biased against events in low-luminosity hosts; 2) rates are compared to parent stellar population properties derived from broad-band photometry, where strong conclusions on the underlying physical cause is difficult; and 3) rates are derived for global host properties that are not necessarily representative of the parent stellar population of any given event. The aim of this proposal is to overcome these issues by obtaining MUSE host-galaxy observations, enabling spectroscopic characterisation of both the whole galaxy and its individual components, of a complete sample of CC SNe (run A) from the all-sky, host-unbiased ASAS-SN survey. In addition, we include a sample of TDE hosts (run B). ASAS-SN has discovered a large fraction of the closest and best characterised TDEs, and studies of TDE hosts have revealed a surprising preference for post-starburst galaxies. We will constrain the rate of TDEs relative CC SNe and we will probe the dependence of TDE rates as a function of population age and metallicity.

B – Immediate Objective: MUSE observations will be obtained for the host galaxies of 89 CC SNe (52 SNe II, 18 SE-SNe, and 9 interacting SNe) and 10 TDEs. The SNe and TDEs forming our host sample have significant follow-up observations, meaning that type classifications and subsequent light curve and spectral evolution can be quantified. These observations will enable characterisation of those host galaxies both on a global scale and on an individual parent stellar population scale (i.e. at the exact explosion site of each transient). Specifically, we will answer the following questions:

1) What is the total CC SN rate in the local Universe relative to the SF rate and stellar mass content? (Using the total SF rate and stellar mass derived for the un-biased host samples.)

2) Is there a discrepancy of CC SNe relative to that implied by the SF rate that suggests a significant number of failed explosions? (Therefore constraining the black-hole formation rate and the 'explodability' of massive stars.)

3) What is the relative rate of hydrogen-rich (II) to hydrogen-poor (SE, IIb, Ib, Ic) events as a function of parent stellar population age and metallicity? (Using both global host properties and SN-explosion site properties.)

4) What is the fraction of SF within low-luminosity galaxies that is missed by galaxy surveys? (Implied by CC SN discoveries in such galaxies.)

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

5) Do TDEs have a clear preference for post-starburst galaxies and how homogeneous are the local environments? (Through analysis of both the global and local properties of TDE hosts.)

6) What is the rate of TDEs compared to that of CC SNe? (What does this imply for the progenitor populations of TDEs?)

A MUSE sample of CC SN and TDE hosts will enable these questions to be investigated in unprecedented detail. Finally, this data will provide a gold mine for further study; it will be extremely useful for studies of galaxy dynamics, stellar populations and chemical evolution, and hence we expect many other projects to spawn from the proposed dataset. The AMUSING project has run for 6 semesters (plus data being collected for P101, and observations planned for P102). The main purpose of this project is to perform environmental analyses of SNe. The project has already published 10 papers (Sánchez et al. 2015 A&A, 573, A105; Galbany et al. 2016, MNRAS, 455, 4087; Prieto et al., 2016, ApJ, 830, 32; Sánchez-Menguiano et al., 2016, ApJ, 830, 40; Krühler et al., 2017, A&A, 602, A85; López-Cobá et al., 2017, ApJ, 850, 17; Lyman et al., 2018, MNRAS, 473, 1359; Sánchez-Menguiano et al., 2018, A&A, 609, 119; Anderson et al., 2018, NatAs, 2, 574; Galbany et al., 2018, MNRAS, 479, 262), and many other projects are currently ongoing.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: Our targets can be observed in any lunar phase as this project is a 'filler' program.

Time Justification: (including seeing overhead) Our proposed MUSE observations aim to detect and measure the strength of H II region emission lines throughout target galaxies, together with narrow absorption features seen on top of the galaxy continuum. To estimate exposure times, we assume a typical r-band surface brightness of 21 mag per arcsec^2 for faint HII regions (James et al. 2004). We then use the MUSE ETC to estimate our required exposure times. We assume an 'Infinitely extended source' and the HII region template (at a redshift of 0.05) together with an r-band surface brightness of 21 mag per arcsec^2. As a 'filler' proposal we set conditions to 7 days from new moon with an airmass of 1.4 and seeing 1.5″.

In order to remove the edges of each IFU on the detector (artifacts of the image slicer) it is best to combine observations with all four 90 degree angles. With 4×550 second exposures the ETC gives a S/N of ∼5 in the continuum, which translates to a S/N of more than 100 for all the emission lines we wish to detect (e.g., Hα, [NII], [O III], Hβ). In many galaxy regions we will obtain much higher S/N in the continuum, and this will allow more detailed analysis of stellar populations, using absorption line indices as an indicator of stellar metallicities in place of the gas phase values. This is required for the small number of elliptical galaxies expected in our sample. Together with 2×220 second sky exposures and overheads, this totals roughly 1 hr per galaxy.

Most galaxies in our sample are covered by one MUSE pointing, so we require 99 hrs to observe our sample of 99 host galaxies. However *as a 'filler' proposal, any amount of data obtained will be beneficial to our project.*

We have previously obtained MUSE data with very similar conditions/observing strategy to that outlined above, and with the above exposure times we are able to make the necessary measurements. We have already published several papers based on these data (see publications section). Our team has experts on the reduction, analysis and interpretation of IFS galaxy observations, hence, while IFS data and their analysis can sometimes prove somewhat daunting, our team provides all the required knowledge to fully exploit this rich data set.

These data will remain in the archive as a legacy for future extragalactic studies.

8a. Telescope Justification:

MUSE at the VLT is the only currently available IFU instrument that has a FoV of sufficient size to cover the majority of our targets, while at the same time having high spatial resolution, high sensitivity, and being extremely efficient, hence enabling targets to be observed in a relatively small amount of time.

We stress here that even in relatively bad seeing conditions (in which the data will sometimes be observed, given the 'filler' nature of our proposal) we will still have the potential to unravel kinematic and population substructure in these galaxies over a large FoV. Indeed, even in bad seeing conditions these data will still be a better position to probe SN environments and galaxy characteristics than any current or past IFU survey (SAURON, ATLAS3D, CALIFA, SAMI, MaNGA).

9b. Observing Mode Justification (visitor or service):

Targets are observable throughout the semester, and as this is a 'filler' program, service mode is required.

8c. Calibration Request:

Standard Calibration

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

099.D-0022: 35hr from 99hr SM MUSE executed (P.I. Galbany); analysis ongoing;
299.D-5040: 2.2hr SM FORS2 (P.I. Gutierrez); publication in prep;
100.D-0326: 9.6hr from 20.8hr SM VIMOS executed (P.I. Kuncarayakti); reduction/analysis ongoing;
100.D-0341: 23hr from 85hr SM MUSE executed (P.I. Kuncarayakti); reduction/analysis ongoing, publication in prep;
101.D-0748: 99hr SM MUSE (P.I. Kuncarayakti); observations ongoing;
2101.D-5023: 9hr SM XShooter and FORS2 (P.I. Leloudas); 1 publication accepted, Anderson et al. (2018);
102.D-0356: 50hr SM FORS2 (P.I. Kuncarayakti); observations not yet started;
102.D-0095: 99hr SM MUSE (P.I. Anderson); observations not yet started

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.

No

9b. GTO/Public Survey Duplications:

No

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

In **bold** those publications using MUSE data)
- Galbany, et al., 2018, ApJ, 855,107: PISCO: The PMAS/PPak Integral-field Supernova Hosts Compilation
- **Kuncarayakti, et al., 2018, A&A, accepted: Constraints on core-collapse supernova progenitors from explosion site integral field spectroscopy**
- **Lyman, et al., 2018, MNRAS, 473, 1359: Investigating the diversity of supernovae type Iax: a MUSE and NOT spectroscopic study of their environments**
- Moreno-Raya, et al., 2018, MNRAS, 476, 307: Elemental gas-phase abundances of intermediate redshift type Ia supernova star-forming host galaxies
- **Sánchez-Menguiano, et al., 2018, A&A, 609, A119: The shape of oxygen abundance profiles explored with MUSE: evidence for widespread deviations from single gradients**
- **Lopéz-Cobá, et al., 2017, ApJL, 850, L17: Serendipitous Discovery of an Optical Emission-line Jet in NGC232**
- **Krühler, et al., 2017, A&A, 602,A45: Hot gas around SN1998bw: Inferring the progenitor from its environment**
- **Galbany, et al., 2016, MNRAS, 455, 4087: Characterizing the environments of supernovae with MUSE**
- **Kuncarayakti, et al., 2016, A&A, 593, A78: Unresolved versus resolved: testing the validity of young simple stellar population models with VLT/MUSE observations of NGC 3603**
- **Prieto, et al., 2016, ApJL, 830, L32: MUSE Reveals a Recent Merger in the Post-starburst Host Galaxy of the TDE ASASSN-14li**
- **Sánchez-Menguiano, et al., 2016, ApJL, 830, L40: Evidence of Ongoing Radial Migration in NGC 6754: Azimuthal Variations of the Gas Properties**

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	ASASSN-16fq	11 20 19.09	12 58 57.2	1			IIP	
A	ASASSN-17qp	20 28 49.80	-04 22 57.3	1			II	
A	SN2017bzb	22 57 17.30	-41 00 57.6	1			II	
A	ASASSN-16fp	21 59 04.14	18 11 11.0	1			Ib/c-BL	
A	ASASSN-16cc	05 46 23.80	-52 05 18.5	1			II	
A	ASASSN-16ab	11 55 04.20	01 43 07.2	1			II	
A	ASASSN-16at	12 55 15.50	00 05 59.7	1			II	
A	SN2016C	13 38 05.30	-17 51 15.3	1			IIP	
A	ASASSN-17ny	08 15 43.38	-28 51 19.8	1			II	
A	ASASSN-16bm	11 51 56.24	-13 25 03.1	1			II	
A	SN2017ivu	15 36 32.70	16 36 19.4	1			IIP	
A	ASASSN-14az	23 44 48.05	-02 07 02.1	1			IIb	
A	ASASSN-15oz	19 19 33.54	-33 46 01.4	1			II	
A	SNhunt327	01 22 11.73	00 57 07.8	1			II	
A	ASASSN-15bd	15 54 38.33	16 36 38.1	1			IIb	
A	ASASSN-15tw	12 50 28.05	-10 50 29.1	1			IIP	
A	ASASSN-15kz	13 37 18.67	-28 39 23.5	1			IIP	
A	ASASSN-17he	09 45 48.36	-14 22 05.6	1			II	
A	SN2014dw	11 10 48.41	-37 27 02.2	1			II	
A	SN2015an	08 24 15.02	-18 46 28.1	1			II-pec	
A	PSNJ2246050	22 46 05.04	-10 59 48.4	1			Ib	
A	ASASSN-15hs	15 33 34.31	-78 07 23.4	1			IIn	
A	ASASSN-16al	15 00 27.47	-13 33 09.0	1			IIP	
A	SN2017cjb	12 53 50.45	09 42 17.7	1			II	
A	ASASSN-15jp	10 11 38.99	-31 39 04.0	1			II	
A	SN2018dfg	14 06 34.70	-05 27 02.9	1			IIb	
A	ASASSN-15ng	13 51 31.65	-48 04 33.7	1			IIP	
A	ASASSN-15qh	22 45 13.22	-22 43 39.8	1			II	
A	ASASSN-14dq	21 57 59.97	22 16 08.1	1			II	
A	PSNJ2025038	20 25 03.86	-24 49 13.3	1			Ic	
A	ASASSN-16jt	22 19 49.42	-40 40 04.6	1			IIn-09ip	
A	AT2018cuf	21 16 11.57	-64 28 57.3	1			II	
A	SN2014ce	23 27 40.86	23 35 21.4	1			II	
A	PSNJ0919528	09 19 52.86	-68 54 41.9	1			II	
A	SN2015ap	02 05 13.32	06 06 08.4	1			Ib	

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

Target Notes: CC SN hosts in run A and TDE hosts in run B. The transient type is listed in the last column.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
103	MUSE	A	WFM-NOAO-N	-
103	MUSE	B	WFM-NOAO-N	-

6b. Investigators:

...continued from box 6a.

J.	Anderson
S.	Bose
S.	Dong
F.	Förster
J.	Falcón-Barroso
L.	Galbany
S.	González-Gaitán
T.	Holoien
P.	James
C.	Kochanek
H.	Kuncarayakti
J.	Lyman
E.	Perez
J.L.	Prieto
F.	Rosales-Ortega
S.	Sánchez
B.	Shappee
K.	Stanek

11a. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
	...continued from box 11.							
A	ASASSN-16eh	15 40 29.23	00 54 36.4	1			II	
A	LSQ15xp	11 32 42.79	-16 44 01.2	1			IIP	
A	ATLAS17bja	11 23 30.78	-08 39 11.8	1			II	
A	ASASSN-15tu	22 34 02.58	-32 23 53.6	1			IIb	
A	ASASSN-15lx	20 36 05.24	-73 06 32.4	1			IIn	
A	ASASSN-15ir	10 48 30.30	-21 38 07.9	1			II	
A	SN2015W	06 57 43.03	13 34 45.7	1			II	
A	ATLAS17lsr	08 49 41.07	-08 05 31.3	1			II	
A	SN2017jbj	00 48 05.42	-02 47 22.4	1			II	
A	ASASSN-16gy	02 21 22.77	16 33 54.6	1			II	
A	ASASSN-14ma	23 55 09.13	10 12 54.2	1			IIP	
A	PSNJ1828582	18 28 58.23	22 54 10.6	1			IIb	
A	ASASSN-16ba	09 42 29.22	-16 58 26.9	1			II	
A	ATLAS17cnz	09 57 03.89	-07 52 51.1	1			IIP	
A	SN2015ay	01 09 46.77	13 18 28.9	1			II	
A	SN2018cow	16 16 00.22	22 16 04.8	1			Ic-BL?	
A	SN2015bf	23 24 49.03	15 16 52.0	1			IIn	
A	SN2018ie	10 54 01.06	-16 01 21.4	1			Ic	
A	SN2016P	13 57 31.10	06 05 51.0	1			Ic-BL	
A	SN2018ddr	13 58 38.47	07 13 01.2	1			IIb	
A	ASASSN-16ai	14 39 44.77	23 23 42.5	1			IIP	
A	PSNJ2241147	22 41 14.79	-21 47 42.1	1			Ib	
A	ASASSN-15ta	20 29 33.35	-61 57 03.7	1			Ib	
A	ASASSN-15ln	00 53 41.35	18 05 29.0	1			II	
A	ATLAS17czi	07 54 13.07	21 47 36.49	1			IIn	
A	ASASSN-15bb	13 01 06.38	-36 36 00.2	1			II	
A	ASASSN-16go	13 02 44.26	-26 56 26.8	1			II	
A	ASASSN-16in	04 59 30.07	-28 51 39.4	1			IIn	
A	ASASSN-15lv	01 58 59.71	-32 22 18.5	1			IIb	
A	MASTER_OT	23 00 24.63	01 37 36.8	1			Ib	
A	ASASSN-15fi	16 31 48.93	20 24 38.8	1			II	
A	ATLAS17lsn	00 03 50.58	-11 28 28.8	1			IIn	
A	SN2017grn	23 31 53.60	-05 00 43.4	1			II	
A	ASASSN-15fz	13 35 25.14	01 24 33.0	1			II	
A	MASTER_OT	14 09 58.91	17 45 49.4	1			IIP	
A	ASASSN-17fy	09 03 32.47	-21 20 02.7	1			IIn	
A	ASASSN-16dm	11 37 20.64	-04 54 36.8	1			IIP	
A	ASASSN-15kj	01 58 11.58	-39 32 49.1	1			Ibn	
A	ASASSN-18dr	12 25 48.54	04 28 26.3	1			Ic-BL	
A	ATLAS17hpc	13 19 03.90	-02 30 45.8	1			II	
A	SN2016hvu	22 35 55.56	20 19 12.6	1			IIP	
A	ASASSN-17oj	21 44 22.94	-29 54 59.3	1			II	
A	Gaia17chn	03 28 07.94	-56 34 42.0	1			IIP	
A	ASASSN-18oa	01 30 27.12	-26 47 06.0	1			IIn	
B	ASASSN-18pg	16 10 58.77	-60 55 23.2	1			TDE	
B	SDSSJ134244	13 42 44.42	05 30 56.1	1			TDE	
B	ASASSN-15oi	20 39 09.15	-30 45 20.7	1			TDE	
B	ASASSN-18ul	22 50 16.14	-44 51 52.5	1			TDE	
B	SDSSJ095209	09 52 09.56	21 43 13.2	1			TDE	
B	PTF15af	08 48 28.13	22 03 33.4	1			TDE	

Following targets moved to the next page...

11a. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
	...continued from previous page.							
B	PTF09axc	14 53 13.08	22 14 32.3	1			TDE	
B	SDSSJ131122	13 11 22.15	-01 23 45.6	1			TDE	
B	D23H-1	23 31 59.54	00 17 14.6	1			TDE	
B	TDE2	23 23 48.62	-01 08 10.3	1			TDE	