EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME PERIOD: **74A**

To be submitted only to: proposal@eso.org
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 Panel: **B–6**

Dissecting the jet-cloud interaction in PKS B2152-699

2. Abstract

Radio-loud AGN emit power in the form of highly collimated particle jets and Doppler-boosted photon beams as well as a more isotropic radiation field which can be shadowed by an optically thick structure close to the nucleus of the host galaxy. An identification of these two types of anisotropy has led to the development of a broadly successful 'viewing-angle based' unification of radio galaxies, quasars, blazars and BL Lac objects. The nature of the particle jets and the associated photon beams and their effects on the state and energy balance of the surrounding IGM is not well known and is a critical factor in our understanding of the evolution of the IGM over cosmic time. This proposal is to exploit, using moderate resolution integral-field spectroscopy and narrow-band imaging, the best nearby example of a jet-cloud interaction in a radio galaxy to measure the separate effects of the particle and photon interactions and so quantify their relative influence on the surrounding medium.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	74	FLAMES	23h	oct	g	$\leq 0.8''$	CLR	s
B	74	WFI	3.5h	oct	d	$\leq 1.4''$	CLR	s

4. 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. (e.g., indicate here if this is a ToO proposal applying for RRM)

6. Principal Investigator: R. Fosbury (ESO, D, rfosbury@eso.org)

CoI(s): L. Binette (UNAM, OTHER), A. Gilbert (MPE, D), R. Morganti (Dwingeloo, NL), T. Oosterloo (Dwingeloo, NL), C. Tadhunter (Sheffield, UK), G. Verdoes Kleijn (ESO, D), D. Worrall (Bristol, UK)

7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

8. Description of the proposed programme

A) Scientific Rationale: The radiation pattern emerging from a radio loud AGN is characterised by two kinds of anisotropy: an *extrinsic* effect due to the shadowing by an opaque disk or 'torus' and an *intrinsic* effect caused by Doppler-boosted emission from bulk relativistic motion in the bi-polar jets. This latter process, while it may radiate only a small fraction of the bolometric luminosity of the source, can result in high photon densities and very high apparent luminosities when seen from close to the direction of bulk motion, as in *BL Lac* objects and *blazars*. The nature of the relativistic jets that are the origin of these photon beams can be studied using different approaches ranging from direct measurements of the broad-spectrum synchrotron radiation from electrons within the jets to the effect they have on the surrounding material both 'within' and 'outside' the host galaxy. For those sources where the jet axis lies close to the plane of the sky, the Doppler boosting renders us blind to the beamed photons although their effects can become apparent when they illuminate material in their path. A gas cloud crossing the axis of the jets can be used as a 'photon counter' and thus allow the comparison of the beamed photon luminosity to other jet properties. We expect the emission line ratios resulting from beam photoionization to reflect the difference in its ionizing SED from that of the intrinsically isotropic component.
The objective of this proposal is to take a major step forward in the already extensive study (Tadhunter et al. 1987, di Serego Alighieri et al. 1988, Tadhunter et al. 1988, Fosbury et al. 1998) of the brightest, most highly excited and most accessible of these jet-cloud interactions. The radio galaxy PKS B2152-699 (z =0.0282) shows a highly ionized cloud (HIC) at a projected distance of 8kpc along its radio axis. The HIC is detected from radio to X-rays and, in many ways, mimics the properties of an AGN itself. By using integral field spectroscopy at a higher resolution than previous work, of the interaction site, we will obtain the data necessary to disentangle the effects of the particle jet from those of the boosted photons emitted from within it. A knowledge of the properties of the jets and photon beams has a broad relevance to the studies of AGN environments since they are capable of ionizing gas, and possibly influencing the rate and location of star formation, on scales of hundreds of kpc from the host resulting in phenomena that are observable at high redshifts.

B) Immediate Objective: Our first objective is to map, at moderately high spatial and spectral resolution using FLAMES/ARGUS, the region containing the HIC, which is the principal jet-cloud interaction site. The combination of optical, radio and X-ray images (Fig. 1) shows a clear spatial separation between the dominant X-ray and radio components which we would expect to see reflected in the optical spectroscopic properties of the HIC sub-components. Such a radio - X-ray separation is also seen in other objects, e.g. Cen A (Hardcastle et al. 3003). The currently-known relationship between the optical and radio components is given schematically in Fig. 2. From existing low resolution spectroscopy (Tadhunter et al. 1988) we know that the cloud emits a strong coronal [Fe X] line, particularly close to the peak of the integrated optical emission. Most of the emission is in lines with a FWHM of 160±50 km s^{-1} but the [O III] exhibits a blue wing extending to 3000 km s^{-1}. Our observations are designed to give us measurements of critical diagnostic emission lines for different kinematic components. The choice of wavelength regions to be observed is based on the requirement to measure the critical line ratios that indicate gas kinetic temperature, electron density and ionization state. An additional requirement is to include lines that are sufficiently strong to enable the identification and measurement of different kinematic components. From existing observations we have no constraints on the presence of regions of low velocity dispersion which could indicate the presence of quiescent, unshocked, photoionized gas. We are particularly interested in the measurement of the coronal lines in order to establish their emission mechanism and how it relates to the X-ray map. Our previous studies have detected lines of [Ca V], [Fe VII] and [Fe X]. In addition to re-observing the [Fe X] (6374Å IP=235eV), we propose to extend the search to [Fe XI] (7891Å IP= 262eV), [Ar XI] (6917Å IP=478eV) and [S XII] (7611Å IP= 504eV).
The second objective is to search for evidence of cloud illumination further out along the jet axis. We have already detected, using EMMI narrow-band imaging, several [O III] - emitting clouds which are confined to within about ten degrees of the jet axis, the furthest of which (limited by the size of the imaging field) is some 80kpc from the galaxy (Fig. 3, Morganti & Fosbury, unpublished). A low resolution spectrum of one of these clouds shows it to have the redshift of the host galaxy and a very high [O III]/H_β ratio. We therefore propose a wider field (2.2m WFI), narrow-band search for [O III] - emitting clouds in order to map a projection of the 'polar diagram' of the beamed ionizing radiation field.
We already have an extensive dataset on this unique source, including HST, Chandra, ROSAT, ATCA and 4m-class optical imaging and spectroscopy. By studying the jet/beam - cloud interactions both 'within' and well outside the host galaxy at unprecedented spatial and spectral resolution, we will, in combination with state-of-the-art ionization modelling, be able to discriminate the complex interplay between the different modes of energy transport in a radio galaxy jet.

References

Tadhunter, C. N., Fosbury, R. A. E., Binette, L., Danziger, I. J., & Robinson, A., "Detached nuclear-like activity in the radio galaxy PKS 2152 69", 1987, Nature 325, 504-507.
Tadhunter, C. N., Fosbury, R. A. E., di Serego Alighieri, S., Bland, J., Danziger, I. J., Goss, W. M., McAdam, W. B., & Snijders, M. A. J., "Very extended ionized gas in radio galaxies. IV - PKS 2152-69", 1988, Monthly Notices of the Royal Astronomical Society 235, 403-423.

8. Description of the proposed programme (continued)

di Serego Alighieri, S., Courvoisier, T. J.-L., Fosbury, R. A. E., Tadhunter, C. N., & Binette, L., "A blue, polarized continuum source near radio galaxy PKS2152-69", 1988, Nature 334, 591-593.
Fosbury, R. A. E., Morganti, R., Wilson, W., Ekers, R. D., di Serego Alighieri, S., & Tadhunter, C. N., "Radio jet interactions in the radio galaxy PKS 2152-699", 1998, Monthly Notices of the Royal Astronomical Society 296, 701-708.
Hardcastle, M. J., Worrall, D. M., Kraft, R. P., Forman, W. R., Jones, C., & Murray, S. S., "Radio and X-Ray Observations of the Jet in Centaurus A", 2003, Astrophysical Journal 593, 169-183.

C) Telescope Justification: FLAMES/ARGUS is the only instrument available for this type of observation offering a sufficiently high velocity resolution to resolve kinematically quiescent gas. Spatial coverage is perfect. For the imaging, we choose the telescope that gives us the max FOV and has a suitable filter combination.

D) Observing Mode Justification (visitor or service): This is a reasonably small programme using two telescopes in 'point-and-shoot' mode. It is ideal for service observations. We are, however, willing to attempt all or part of the programme in visitor mode.

E) Strategy for Data Reduction and Analysis: The imaging data analysis is straightforward and we are well-equipped to carry it out. For the integral field spectroscopy, members of our team have a strong interest in this type of data and are well positioned to work with local experts at ESO/ECF. Our team contains expertise in the techniques of photo- and shock-ionization as well as in non-thermal jet emission mechanisms at all wavelengths. We were the discoverers of this source many years ago and have an extensive publication record on it. We will use the imaging data to produce a projection of the 'polar diagram' of the beamed emission on the assumption that the clouds are photoionized by this component. The analysis of the HIC will involve the use of archival (public) Chandra, HST and ROSAT data as well as our published radio image. The spatial variations of emission line ratios and velocity widths will enable us to identify the nature of the ionization mechanism at different locations and to measure the beam and jet power.

8. Attachments (Figures)

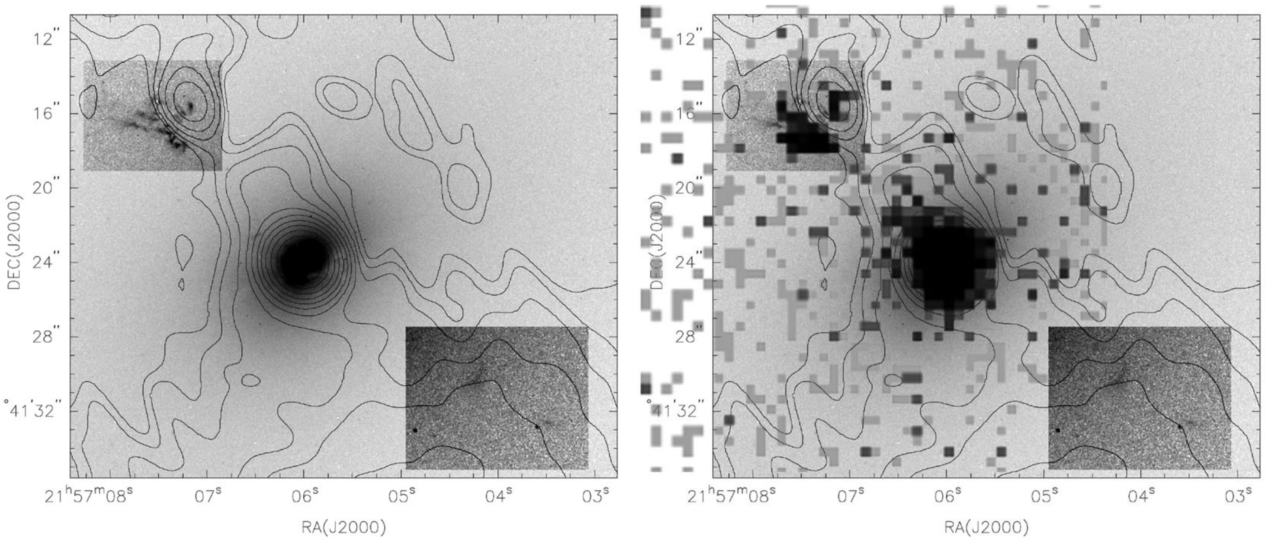

Fig.1 - PKS B2152-699

Fig.1 (a) 6cm radio contours from the ATCA overlayed on the HST PC F606W image of PKS B2152-699 from Fosbury et al. (1998). (b) The same as (a) but with a quick-look Chandra X-ray image superimposed. The Chandra data (taken from the public archive) contain about 2700 counts in the galaxy and several hundred in the HIC. It is clear that the dominant HIC X-ray component is displaced from the radio peak by more than 2 arcsec, making it feasible to look in detail at the spectroscopic differences between these regions.

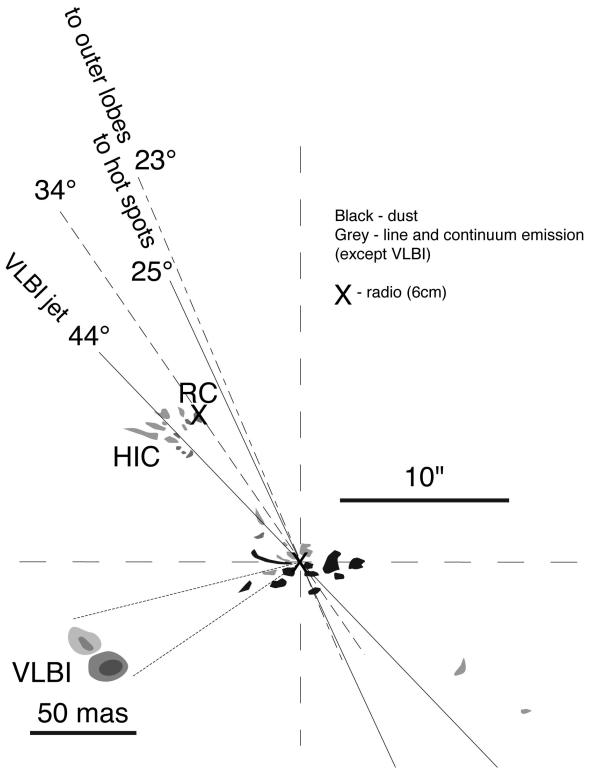

Fig.2 - Cartoon of the radio and optical components

Fig. 2 A cartoon showing the positions and position angles of the various radio and optical sources associated with the nuclear and HIC regions of PKS B2152-699. Note that the VLBI jet points towards the apex of the cloud distribution in the HIC and not to the associated radio component.

8. Attachments (Figures)

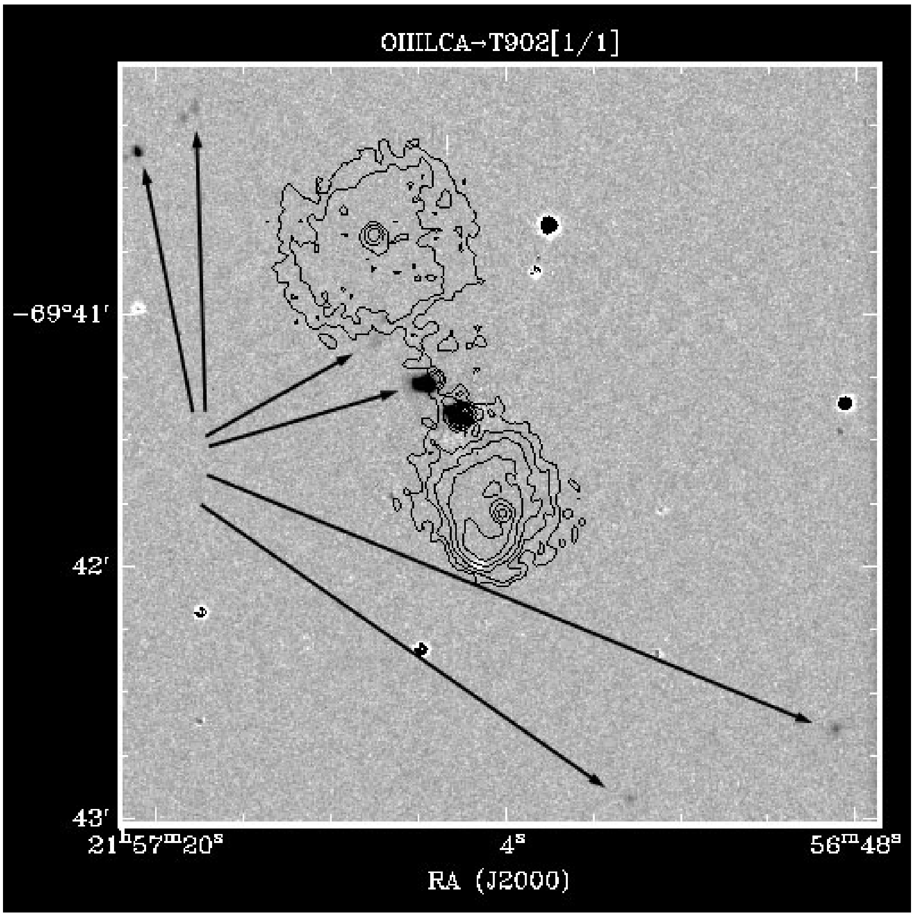

Fig.3 - 6cm radio contours over [O III] image

Fig. 3 The ATCA 6cm radio contours overlayed on a continuum subtracted, narrow band [O III] image taken with EMMI on the ESO NTT (Morganti, Osterloo & Fosbury, Priv. Com.). Note the [O III] clouds marked with arrows, in addition to the HIC, along the jet axis. Bright stars in the field appear as (black) saturated regions.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: The FLAMES observations are at sufficiently high spectral resolution that they can be executed in grey time. The 'on-band' WFI observations with both filters will be dominated by sky noise and so, for these, we request dark time.

Time Justification: (including seeing overhead) **Run A:** we propose FLAMES/ARGUS IFU spectra using the 0.52" size and a $11.5'' \times 7.3''$ FOV, giving full coverage of the HIC. We will use the $R = 11000$ mode which gives a velocity resolution of $\sim$ 27km/s.. We will use five standard settings to cover the lines listed below. Setup LR02 covers 4072Å[S II], Hδ , Hg4340 (flux 0.41 Hβ), [OIII]4363. Setup LR03 covers HeII4686. Setup LR04 covers [OIII]4959,5007. Setup LR06 covers [OI]6300,6370, [FeX]6374 with OI6370 OI (flux 0.14 Hβ), Hα and [NII]6584, [SII]6723 and [ArXI]6917. Finally, setup LR07 covers [FeXI]7891 and [SXII]7611. We calculated exposure times based on the fluxes given in Tadhunter et al. (1988) relative to a Hβ flux of 2.3×10^{-15}erg/cm^2/s through a 4×4.6 arcsec^2 aperture. We used our HST imaging to determine the flux distribution on scales of the FLAMES IFU apertures. In order to detect the expected faintest lines at each setting we derive at a typical integration time of $\sim$4hours per setting. Including overheads, we arrive at a total execution time of 23hours.
Run B: We propose to take WFI on- and off-band imaging to map the [OIII] emitting cloud distribution. We will use the 516/16 (no. 871) filter as on-band image and the V/89 broad-band (no. 843) filter as off-band image. A typical cloud total [OIII] flux of 10^{-16} erg/s/cm^2 is inferred from the EMMI imaging and EFOSC spectrum. We computed exposure times by expanding the ETC to include the 516/16 filter, taking into account telescope, instrument and filter characteristics as currently available. In 3.5hours of exposure time through the 516/16 filter and 0.5hour through the V-band filter we will be able to detect a typical cloud with a signal-to-noise ratio of $\sim$ 5. We require dark time because the sky flux is the dominant noise contribution. Taking into account overheads for pointing, guide star acquisition, focussing and filter change we arrive at a total execution time of 4.5hours.

Calibration Request: Standard Calibration

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

RAEF: Co-I on GOODS Large Programmes
AG P72 has led two VLT programs to study the nebular kinematics, and X-ray properties of super star clusters. Observation are currently underway.
CNT: 70.B-0663, 3N, NTT/EMMI. Project to detect broad quasar-like lines in nearby FRI radio galaxies. In spite of some bad weather, useful data were obtained for some objects. The data are currently being reduced.
71.B-320, 2N, UT1/FORS1. Project to use polarimetric observations of the [OIII] emission lines to detect scattering outflows in powerful radio galaxies. A paper on the preliminary results will be submitted in Summer/Autumn 2004.
71.B-616, 2N, UT4/FORS2. Project to investigate the properties of the young stellar populations in powerful radio galaxies. The data are fully reduced, and the first paper presenting the results of the analysis is in preparation.

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

Villar-Martín, M., Vernet, J., di Serego Alighieri, S., Fosbury, R., Humphrey, A., & Pentericci, L., "Kinematically quiet haloes around z˜ 2.5 radio galaxies. Keck spectroscopy", 2003, MNRAS 346, 273-294.

Taylor, M. D., Tadhunter, C. N., & Robinson, T. G., "The structure of the narrow-line region in Cygnus A", 2003, MNRAS 342, 995-1008.

Morganti, R., Oosterloo, T. A., Tinti, S., Tadhunter, C. N., Wills, K. A., & van Moorsel, G., "Large-scale gas disk around the radio galaxy Coma A", 2002, A&A 387, 830-837.

Robinson, T. G., Tadhunter, C. N., & Dyson, J. E., "Overpressured emission-line clouds in the haloes of powerful radio galaxies", 2002, MNRAS331, L13-L18.

Dopita, M. A., Groves, B. A., Sutherland, R. S., Binette, L., & Cecil, G., "Are the Narrow-Line Regions in Active Galaxies Dusty and Radiation Pressure Dominated?", 2002, ApJ 572, 753-761.

Cecil, G., Dopita, M. A., Groves, B., Wilson, A. S., Ferruit, P., Pécontal, E., & Binette, L., "Spatial Resolution of High-Velocity Filaments in the Narrow-Line Region of NGC 1068: Associated Absorbers Caught in Emission?", 2002, ApJ 568, 627-638.

Worrall, D. M., Hardcastle, M. J., Pearson, T. J., & Readhead, A. C. S., "The relationship between the X-ray and radio components in the compact steep-spectrum quasar 3C 48", 2004, MNRAS 347, 632-644.

Hardcastle, M. J., Worrall, D. M., Kraft, R. P., Forman, W. R., Jones, C., & Murray, S. S., "Radio and X-Ray Observations of the Jet in Centaurus A", 2003, Astrophysical Journal 593, 169-183.

Birkinshaw, M., Worrall, D. M., & Hardcastle, M. J., "The X-ray jet and halo of PKS 0521-365", 2002, MNRAS 335, 142-150.

Verdoes Kleijn, G. A., Baum, S. A., de Zeeuw, P. T., & O'Dea, C. P., "Core Radio and Optical Emission in the Nuclei of nearby FR I Radio Galaxies", 2002, AJ 123, 1334-1356.

plus others

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT(hrs)	Mag.	Diam.	Additional info	Reference star
A	PKS2152-69-HIC	21 57 08	-69 41 16	23			HIC at 10" from galaxy	
B	PKS2152-69 [OIII] clouds	21 57 06	-69 41 23	3.5				

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
74	FLAMES	A	GIRAFFE	standard setup LR02 427.2
74	FLAMES	A	GIRAFFE	standard setup LR03 479.7
74	FLAMES	A	GIRAFFE	standard setup LR04 543.1
74	FLAMES	A	GIRAFFE	standard setup LR06 682.2
74	FLAMES	A	GIRAFFE	standard setup LR07 773.4
74	WFI	B	imaging	V/89, 516/16