Monitoring southern hemisphere *Fermi*-detected AGNs with the Radio Interferometer in New Zealand

1 Introduction

Analysis of *Fermi* LAT data revealed that more than one half of detected points sources are active galactic nuclei (AGNs). The intrinsic property of AGNs is variability at scales from days to decades at all wavelengths from radio to hard γ-rays. One of the major outcomes of *Fermi* mission is monitoring of γ-ray loud AGNs. High energy light curves together with the spectrum in MeV–GeV range and position localisation is the legacy data product of the mission. In order to enhance the outcome of the *Fermi* mission, matching monitoring programs at other wavelengths are needed. The most comprehensive matching program is the The OVRO 40-Meter Telescope Monitoring Program (Richards et al., 2011) that observes for 10 year a list of 1835 AGNs at declinations $> -20^\circ$, including 930 γ-rays associated sources from FL8Y catalogue of point sources with a cadence of 2 times a month. The SED of AGNs has two distinctive broad peaks: one spanning from radio through optical to soft X-ray and another spanning from KeV to TeV. Emission mechanism of two peaks is different. Therefore, monitoring in radio does not duplicate monitoring in γ-ray range, but provides additional complementary information.

Radio/γ-ray monitoring data are used for a statistical study of the AGN population and for case studies of selected sources. The focus of the statistical studies is on deriving the radio and radio/γ-ray observational properties of the AGN population, including a) the radio variability properties of the AGN population, their dependence on redshift, spectral classification, luminosity, etc; b) any differences between the radio properties of *Fermi* detected AGNs and AGNs with similar radio luminosity which have not been detected by *Fermi*; c) the properties of cross-correlations between radio and γ-ray flares. The focus of case studies is to derive time delay between γ-ray and radio flares and detect periodicities and peculiarities in light curves.

The OVRO blazar monitoring program is highly successful: by 2018 over one hundred peer-reviewed and proceedings papers used the light curves from that program. But geography sets the limit of the program: sources with declinations below -20°, i.e. 1/3 of the sky are excluded.

2 New observing capabilities in the southern hemisphere

The majority of radio telescopes is located in the northern hemisphere. Few existing telescopes are over-subscribed. To make things worse, budgeting restriction for last 2–5 years reduced the amount of time existing radiotelecopes at the south are available to work for sciences, f.e. Parkes and Mopra. In this situation a large dedicated program on existing radioastronomical facilities is highly problematic. Our group spend XXX years for converting a former telecommunication 32-m dish in Warkworth (latitude: -36.4°, longitude: 174.7°), New Zealand, to a working radiotelescope. In 2014 the first successful results at 6.7 GHz receiver were obtained (Petrov et al., 2015) and in August 2017 first successful observations using a 8 GHz receiver were made. There is a smaller 12m radio-telescope designed for geodesy also equipped with a 8 GHz receiver at a distance of 185.226 meter from the 32m telescope. Since August 2017 both telescopes are participating in VLBI observations at X-band (8 GHz). Analysis of VLBI results at 185m long baseline showed excellent performance: residual phase delays over 24 hour period has a scatter of 5 ps, i.e. phase is stable with rms of 15° and fringe amplitude is also stable.

This prompts us to propose a program of using a former telecommunication dish and the geodetic radio telescope as a radio interferometer suitable for source flux density monitoring. We measured the sensitivity of the interferometer and found that we can determine flux density of a 50 mJy source with the thermal noise of 5 mJy using 8 minute integration time.

3 Proposed work

We propose to run a program of monitoring **all** *Fermi* associated AGNs with declinations $< 0°$ with flux densities brighter 50 mJy at 8 GHz with the Radio Interferometer at New Zealand (RINZ) that consists of two radio telescopes 185 meter apart. We have identified 773 such sources in the FL8Y catalogue. Each source will be observed from 1 to 8 minutes, depending on flux density, at the interferometer. We plan to observe two twenty four hour sessions per week, 2500 hours per year. It will require four days to observe the entire list. Thus, our radio monitoring program will provide light curves with a cadence ~ 15 days, close to thgrpe "at provided by the OVRO monitoring program. We reserve a room for ~ 50 more sources that will be added to the program upon a request, for instance, newly detected sources or flaring *Fermi* sources. We intentionally set the overlap with the OVRO program in the declination range of -20° to 0°. The purpose of this overlap is to check consistency of our results with respect to the OVRO monitoring results.

4 Significance of the proposed work

The current OVRO monitoring program covers 2/3 of the sky. Our proposed program will cover 1/3 remaining sky with an overlap of 1/6 with OVRO prorgram. Thus, the all sky γ-ray AGN monitoring mission will have a matching all sky OVRO+RINZ mission with no bright AGN left alone. The merit of the hemisphere bias elimination is the following:

- the risk of losing an important variable source just because there existing montitorin program covers only a part of the sky is eliminated.
- the number of sources for which time delay in radio/γ light curves is known will be increaed by 50%. Such sources are very valuable for case studies. Max-Moerbeck et al. (2014) report 41 such sources. A number of papers were devoted to analysis of light curves of such single sources, for instance (Bhatta, 2017)
- southern radio sky in time domain is mainly an unexplored territory. We experct insteresting discoveries.
- we expect our radio southern monitorinig program will help to launch monitoring at optical wavevelengths in the southern hemisphere creating a multiplication effect.

One can argue that since 59% the Moon area is visible from the Earth, the opposite, invisible side is expected to look the same. Luna–3 mission has demonstrated that this is not the case. Notably, a number of extraordinary *Fermi* detections has happened in the southern hemisphere at declination $< -20°$ and therefore they were not observable by OVRO. A few examples of remarkable events include:

- the gamma-ray burst GRB 080916C ($\delta = -56°38'$) in September 2008. This burst had "the largest apparent energy release yet measured";

- detection and localization a gamma-ray burst in the southern sky designated as GRB 170817A ($\delta = -23°23'$) within 1.7 s of the gravitational wave signal;
- detection a weak gamma-ray burst starting 0.4 seconds after the LIGO event GW150914 ($\delta = -22°$) on September 2015. The odds of such an event being the result of a coincidence or noise is evaluated at a level of 0.2%.

The event GRB 170817A was followed-up by the southern hemisphere telescopes, however, no monitoring in radio spectrum was conducted for these southern sources before or during the corresponding remarkable events, except for the one which was identified with the IceCube neutrino detection. Luckily, concurrently with the most powerful (2 PeV energy) neutrino event HESE-35, dubbed 'BigBird' registered on 4 December 2012 with the IceCube neutrino detector in Antarctica, both *Fermi* and the Long Baseline Array (consisting of radio telescopes in Australia, NZ and SA) monitored the corresponding area of the southern sky. Careful analysis of both *Fermi* and radio observations allowed a high probability cross-identification of the source of the ultra-energetic neutrino with the blazar PKS B1424–418 ($\delta = -41.8°$) — the first ever identification of the source of ultra-energetic neutrinos.

The paper about the northern hemisphere program, (Richards et al., 2011), has collected 197 citations for seven years after publication, and 91 papers peer-reviewed are baeed on usin the light curves. This provides a strong evidence that such a data product is indeed needed to the scientific community. Providing information about radio light curves of 1/3 *Fermi*-detected blazars not monitored by radio hitherto, their variability indices, epochs of flaring events, and their delay with respect to γ-ray flux will enhance the value of the *Fermi* mission, especially its part related to a study of AGNs.

5 Logistics of the proposed program

Observations will be performed in a sequence that minimizes slewing. Integration time will be selected according to expected flux density to have SNR > 20 for weack sourecs and more than 30 for sources brighter 100 mJy. The data will be recorded at 2 Gbps rate in dual-polarizations and transferred via ftp to the computer center of Auckland University for correlation. Then the data will be correlated, fringe-fitted, and calibrated. The estimates of flux density, including all four Stokes parameters, will be made publicly available at the project web site immediately after completion of analysis, i.e. within 5–15 days after observations.

Calibration will be performed by firing the noise diode of the antenna calibration unit before observation of every program source, which is a standard procedure in radio interferometry, by observing amplitude calibrator radio sources, and by observing common sources with the OVRO program. Our goal is to reach 5% accuracy in calibration and 5 mJy error floor. At the moment, only the 30m radiotelescope is equipped with the antenna calibration unit. The second 12m radiotelescope designed for geodesy does not have it. The lack of the antenna calibration unit at the 2nd antenna adversely affects accuracy of calibration, since antenna gain fluctuations at the 12m antenna remain unchecked. Our analysis of VLBI observations with the 12m antenna provided us the estimate of accuracy of the antenna calibration without the noise diode at a level of 20%.

Therefore, we request funds on amount of $30,000 to purchase the antenna calibration unit by the performing organization from the Haystack observatory, MIT that manufactures them. The performing organization will loan the unit to the Auckland university for the duration of this observing program. Using antenna calibration units at both antennas will reduce calibration errors from 20% to 5%, which is typical for radio interferometers. Calibration accuracy 5% is required for scientific analysis of light curves. For comparison, the OVRO program has calibration errors at a level of 2–3%.

Roles of the team members:

- L. Petrov — development of the pipeline of data analysis and calibration; overall management of the project;
- S. Gulyaesv — data analys, management of the Auckland University team;
- S. Weston, T. Natusch — tuning hardware, running the observations;
- two Ackland Universtiy mater level students — running the observations, maintaining the project web site.

We request funds at 0.1 FTE level for the PI, Leonid Petrov, for development of the pipeline of data analysis. No funds are requested for foreign co-investigators. Their labor cost as well as the operational cost of running the interferometer is covered by Auckland University. The total amount of requested funds is $55,000.

This monitoring program will be the most valuable if preformed concurrently with *Fermi* observations. Since the ten year old *Fermi* mission will not last forever, we are hurring up to start the observing program as soon as possible while it is operating. We intentionally set aside from the framework of this proposal scientific interpretation of the monitoring results which we and other users of the RINZ AGN monitoring program will engage. This important work can be done later, but delaying the launch of the southern hemisphere monitoring program we face a risk to lose the opportunity of concurrent *Fermi* observations.

6 Bibliography

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